SPACE LAUNCH OPERATIONS AND CAPACITY MODELING: A SYSTEM DYNAMICS METHODOLOGY FOR ADVANCED ANALYSIS OF THE U.S. EASTERN RANGE

by

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Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degree of
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at the

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ABSTRACT

A prototype computer model was developed to assess the feasibility and potential benefits of a system dynamics approach to calculating space launch operational constraints and range capacity. This research effort concentrated on modeling the U.S. Eastern Range. The current U.S. Air Force Range Capacity Model served as a modeling framework, upon which significant enhancements of analysis capability and fidelity were achieved. Improvements realized by the system dynamics methodology are due to a fundamental transition in modeling technique from a deterministic spreadsheet approach, as utilized by the Air Force, to a more realistic simulation platform. The system dynamics model produces a probabilistic distribution of values rather than a single point solution and does not require the input of an annual launch manifest.

In addition to developing an improved modeling methodology, two analyses of Eastern Range operating conditions were conducted for fiscal year 2001. The first analysis examined the expected operating conditions. The second analysis focused on operating the range under a maximum launch capacity scenario. In comparison to the 30 launches scheduled on the Eastern Range manifest, simulation results suggest range launch capacity as a distribution of values between 49 and 54 launches, with a mean value of 51 launches. Even though the FY01 launch manifest will not utilize the maximum capacity of the range, the model predicts that launch programs will still collectively endure approximately 2,500 calendar hours of wait time before range resources are available to fulfill all requests for range support. The following six range constraint categories were modeled as the primary causes of the unavailability of range support resources: 1) range crew rest, 2) planned restricted periods, 3) range lockdown, 4) rescheduling impact, 5) unexpected range systems maintenance, and 6) single major operation support capability. Range crew rest was determined to have the largest detrimental impact to launch operations efficiency for both the FY01 expected operating conditions and the launch capacity scenario. The relative impacts of the remaining five categories were observed to fluctuate depending on the number of launches and resulting congestion of range operations.

Thesis Supervisor: Dr. Joyce Warmkessel
Title: Senior Lecturer, Department of Aeronautics and Astronautics

"In the real world of irreversible actions and high stakes the need to maintain performance often overrides the need to learn by suppressing new strategies for fear they would cause present harm even though they might yield great insight and prevent future harm."

Dr. John D. Sterman

ACKNOWLEDGEMENTS

A considerable amount of effort and time went into this research, much of which could focus on this thesis topic because of an existing Range Capacity Model. I am thankful for the extraordinary efforts of the 45th Space Wing in its development of the Range Capacity Model, which served as a starting place for my work. In particular, I need to personally thank Darren Buck for his endless assistance and advisement as the primary creator of the Air Force model. In addition, Paul Cotter played a crucial role in advising this work with his operational and modeling expertise.

Although it is not possible for me to specifically name all of the individuals who contributed to this effort, I do wish to acknowledge the technical advisement efforts of Tripp O'Dell, Rick Ort, and Barry Priddy. The entire Lockheed Martin Atlas launch team deserves a special thank you for being my co-op host and providing me with my first real experience with space launch operations.

I would also like to mention the critical assistance I received from Boeing, NASA, Lockheed Martin, Air Force Space Command, and SigmaTech.

Studying at MIT has been an incredibly rewarding experience. The Lean Aerospace Initiative was the sponsor of this research. The support I enjoyed from LAI was incredible and allowed for the research to be done. Specifically I wish to thank Dr. Joyce Warmkessel for being my advisor and thesis supervisor. I also want to thank Professor John Sterman for introducing me to the exciting field of system dynamics.

Finally, I sincerely thank my wife, Galina, to whom this thesis is dedicated. With her constant love and support I was able to accomplish the long hours and intensive work that this effort required.

David H.W. Steare

FORWARD

All journeys of exploration begin with questions.

How many launches can we launch in a year? What is theoretically possible? What are the obstacles to increasing our capacity to launch rockets?

In early 1998, a few of us at Cape Canaveral set out to answer these questions. There was no shortage of opinions on the subject. Range turnaround time, equipment age, safety requirements, schedule congestion, processing discipline, range management… All of these factors could be seen to play a role of some sort, but contributing impacts could not be individually assessed on opinion alone (however expert and grey-haired those opinions may have been). Armed with operational experience on the range, versed in sound system engineering processes, and having had contact with all of the major launch programs, we settled on modeling the Range as our method of answering the aforementioned questions. This approach of the Range as "common denominator" was indeed novel, but made intuitive sense and eventually gained full acceptance (not without teeth-pulling and spear-chucking, but those are stories for another day…).

Attempting to model the operations of the Eastern Range was the first step in trying to define the "forest with the trees". Previous efforts had more or less focused on the launch rates for individual booster programs or space launch complexes, again underscoring the traditionally "stovepiped" conventional wisdom of exploring this subject. Prior to (USAF Lt Gen, retired) Richard C. Henry's Range IPT Report of 1998, which showcased our Range Capacity Model, there had been no integrated, quantitative evaluation of range operations or those multiple factors. The RCM became the "little spreadsheet that could". We recognized, however, that it was only the first step—more efforts would be necessary.

The Eastern Range, Cape Canaveral Air Force Station, and the Kennedy Space Center, all collectively now known as the "Cape Canaveral Spaceport", comprise a unique and fascinating blend of people, policy, technology (or lack thereof), nature, organizations, nationalities, history, personalities, physics, power, sweat, drama, emotion, and dreams. Today's Cape is a microcosm and stepping-stone to tomorrow's vision: multi-agency, multi-corporation, and multinational space transportation. No other spaceport is busier or more diverse. At the center of all of it, like a traffic cop, landlord, and referee all rolled into one, is the Air Force and the Eastern Range.

I am proud to have led much of the early exploration of how this microcosm functions as a whole, and I have gained a greater appreciation of the importance of all of its individual constituents in the process. I am also necessarily proud to have witnessed Dave Steare's evolution of the discourse and his construction of a vastly superior systems dynamics framework capable of evaluating a wider variety of spaceport data and constituents. It is the logical next step, and, in my opinion, worthy of qualifying as a prototype for a "spaceport model". The following paper details this model and the ongoing exploration of an aspect of space transportation that is often overlooked, but which is the fundamental element used by all who wish to launch from the Earth, through the Air, and into Space.

Proficisci Audentius – "To go, set forth, and explore, boldly, audaciously, and often unconventionally."

Darren "Shades" Buck
August 2000

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CHAPTER 1: INTRODUCTION

1.1 Overview of Thesis

The focus of this work is on the development of a methodology to model space launch operations and range capacity. This effort concentrated on the U.S. Eastern Range. The independent modeling research presented in this thesis both utilizes and enhances an existing model developed by the U.S. Air Force. In order to obtain increased capability and improved fidelity, system dynamics was used to introduce a fundamental shift in modeling approach.

Chapter 1 provides the reader with backgrounds on the Air Force range capacity model and the Lean Aerospace Initiative (research sponsor). Following this material is a brief description of the field of system dynamics. The first chapter is completed with a short and worthwhile exercise, intended to introduce readers not trained in system dynamics with the basic skills necessary to read causal loop diagrams.

Chapter 2 outlines the major assumptions and primary variables contained in the system dynamics model. The chapter begins with a description of Eastern Range operations and proceeds with an overview on the organization of the model. In this chapter, the reader is presented with the basic structure of the model. The most significant relationships between model variables are discussed and then illustrated in the form of causal loop diagrams.

Chapter 3 demonstrates how the system dynamics model can be used to perform analysis of launch operations. The first part of the chapter establishes model capabilities and general utility by giving examples of possible model outputs. The remaining section of the chapter is devoted to the analyses of two different Eastern Range scenarios for fiscal year 2001. One analysis reflects the expected operating conditions for FY01. The other analysis corresponds to the scenario of operating the range at maximum capacity conditions for this same time period. Finally, a comparison between the two scenarios is presented.

Chapter 4 examines some of the recent policy implications of "range capacity". Of particular concern is the emergence of the commercial space launch industry during the past decade. The chapter begins with a look at the major roles and responsibilities of the different organizations currently involved with U.S. space launch. The subject of launch capacity is discussed in relation to existing laws and policies as well as the findings of a few recent studies and reports.

Chapter 5 begins with an overall summary of the thesis findings. The first group of findings lists the additional capabilities and improvements accomplished by the system dynamics modeling effort. Then primary results from the analyses of FY01

Eastern Range operating scenarios are presented. These results are followed by related policy findings. The chapter concludes with a list of recommendations.

Chapter 6 includes two appendices. A glossary of specialized terminology is included as well as a listing of works cited.

1.2 Background and the Original Air Force Range Capacity Model

The 45th Space Wing of the U.S. Air Force initiated development of a range capacity model in response to operational issues raised in December 1997 at the Air Force Space Command sponsored Commercial Space Industry Leaders Conference. The initial modeling effort resulted in a functioning model by March 1998. This model was created using Microsoft Excel spreadsheet software and combined a large amount of operational data and experience to calculate annual values of range capacity, measured as the maximum number of possible launches.

The objective of the range capacity model was to 1) develop an Air Force and industry accepted definition of range capacity and the operational variables impacting range capacity; and 2) develop an effective tool for range operational analysis and evaluation. The model was refined, updated, and also adapted for Western Range operational analysis. The modeling team further validated model results by conducting a series of briefings over a period of several months in 1998. These conferences, meetings, and presentations provided multiple opportunities for feedback and commentary.

The range capacity model has played an instrumental role in supporting a number of recent and major studies on national launch operations. It served as the mathematical engine for both the *Range Integrated Product Team Report* and also the *National Launch Capabilities Study*, which was mandated by Congress in the Commercial Space Act of 1998. In addition, the model was used in conducting the *Launch Vehicle Broad Area Review* (BAR) as well as the White House Interagency Workgroup Report, formally titled as *The Future Management and Use of the U.S. Space Launch Bases and Ranges*.

Stemming from significant baseline efforts to integrate and account for the diverse collection of factors that influence range launch capacity, this spreadsheet model established an initial methodology to quantify range capacity. U.S. Air Force Space Command has since adopted this methodology and currently uses it as the standard way of approximating range capacity. The Air Force model relies upon the projected number of annual launches of different vehicle types, obtained from the National Launch Forecast. It uses this forecast to generate the characteristics of an average launch vehicle, called a "generic booster", for each year. The model then determines the amount of range support time associated with a generic booster and uses this value to calculate the maximum number of annual generic booster launches that can be conducted in addition to the launches already existing in the National Launch

Forecast. The model ultimately arrives at values of range capacity by adding those launches already contained within the National Launch Forecast and the maximum number of generic booster launches on a yearly basis.

Following initial consultation with the original developer of the Air Force range capacity model in late summer of 1999, the author began an independent modeling project at the Massachusetts Institute of Technology (MIT), as part of the ongoing Lean Aerospace Initiative program. The focus of this effort was to explore the possibility of applying an advanced system dynamics[1] approach to modeling range capacity. With the invaluable cooperation and input from the key members the Air Force range capacity modeling team as well as additional industry experts, the author was able to successfully develop a prototype next-generation model using system dynamics. The system dynamics model is the subject of this thesis.

It is important to state once again that the system dynamics model utilizes much of the work and many key variable relationships already applied in the existing USAF model. In this sense, the modeling effort of the author has much to owe to the hard work and dedication that was applied in creating the original Air Force range capacity model.

One underlying assumption of both models is that the possible number of annual launches from a single range is a function of the range support requirements for each proposed launch vehicle campaign and the ability of the range to provide this support for each campaign. The fundamental unit of measure chosen to model launch capacity was time.

Launch capacity is derived from the time requirements of the following cumulated factors: launch vehicle operations support durations, effects of scheduling changes, impact of range systems maintenance, planned range downtime, and range personnel workload limitations. The system dynamics model goes beyond the capabilities of the USAF deterministic approach. Rather than simply calculating a single value for the maximum possible number of annual launches, this advanced methodology uses probabilistic methods to determine an entire set of likely scenarios. Results from multiple simulations are then combined to produce a distribution of expected values for launch totals as well as other important operations variables.

1.3 The Lean Aerospace Initiative

The Lean Aerospace Initiative (LAI) was formed in 1993 as a research consortium among the U.S. Air Force, the Massachusetts Institute of Technology, labor unions, and the defense aircraft industry. The concept of "lean" was first documented in the U.S. through the International Motor Vehicle Program in the book *The Machine that*

[1] System dynamics is a modeling methodology founded by Jay Forrester at MIT in 1956 that combines theory and computer simulation while accounting for internal feedback-loop relationships

Changed the World. This earlier research effort focused on the philosophy of a lean production system, as pioneered by the Japanese automobile company Toyota.

Originally called the Lean Aircraft Initiative, the initial LAI partnership focused on exploring whether lean techniques developed within the automotive industry could be adopted to meet the "better, faster, cheaper" demands of America's defense aircraft industry. Five basic principles are combined to form the lean philosophy: 1) specify *value* from the perspective of the end customer, 2) identify the *value stream* for each product, 3) strive for continuous *flow* of the product, 4) let the customer *pull* the product, and 5) strive for *perfection*.

In 1998, the Lean Aircraft Initiative changed its name to the Lean Aerospace Initiative to reflect the inclusion of additional members from government and industry space sectors. In addition, a new Test and Space Operations (TSO) focus team was formed to conduct research on space-related topics. The TSO team is currently engaged in performing research in the areas of lean spacecraft testing, launch operations, and on-orbit operations.

Results from specific research efforts are combined and disseminated to LAI members in various forms. One such product is the Lean Enterprise Model (LEM), which is a tool that encompasses lean principles and practices and presents them as a collection of guidelines and metrics. The LEM is populated by research-based benchmarking data derived from surveys, case studies, and other research activities. It is available online for all members of the research program and can be found with additional information about the Lean Aerospace Initiative at http://web.mit.edu/lean.

1.4 System Dynamics

System dynamics is both a perspective and a set of conceptual tools that enable us to understand the structure and dynamics of complex systems (Sterman 2000). Jay Forrester pioneered the field of system dynamics, based upon control theory and nonlinear dynamics, in 1956 at MIT. With the continual enhancement and availability of high-speed computers, system dynamics is becoming a widely used means of simulating highly complex and dynamic systems.

System dynamics is a modeling methodology that enables the creation of formal computer models. These models can then be used to design more effective policies, operations, and organizations. In recent years, many top companies, consulting firms, and government organizations have implemented system dynamics to study critical issues. Some leading edge universities, such as MIT, currently teach courses in system dynamics. There are a couple of commercially available software programs, which can be used to develop system dynamics models. This research effort utilized *Vensim 4.0*, a software package developed by Ventana Systems. Readers interested in the subject of system dynamics are encouraged to read a recent book authored by Professor John D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World* (published in 2000 by McGraw-Hill).

Although this thesis is not meant to provide the reader with an in-depth comprehension of system dynamics, nor does it strive to develop the associated skills of the reader, it is necessary to understand one tool that is frequently utilized in the construction of system dynamics models. **Causal loop diagrams** (CLDs) are visual illustrations used to represent the feedback structure of systems.

The conventions for creating and reading causal diagrams are simple and straightforward, but must be followed faithfully. An elementary exercise is presented below to introduce the basic skills needed to understand the causal loop diagrams included in later sections of this thesis.

Causal Loop Diagram Exercise

As an example situation, suppose there is a chicken farm. Assume that there is limited space available on the farm to raise chickens and for the chickens to lay eggs. Suppose that each day the farmer has only one bucket of food available to feed all of the chickens. Figure 1.1 depicts a causal loop diagram showing a suggested model structure for the example chicken and egg situation.

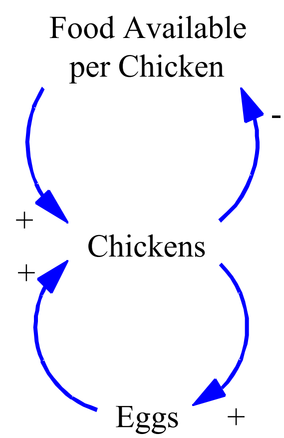


Figure 1.1: Causal Loop Diagram

Variables are represented by words in a causal loop diagram. This example contains a total of three variables. These variables are the number of *'Chickens'*, the number of *'Eggs'*, and the amount of *'Food Available per Chicken'*.

Arrows designate mathematical relationships between variables. Let's begin by examining only the relationship between *'Chickens'* and *'Eggs'*. The head of an arrow points to a variable that is dependent upon, or influenced by, the variable found at the tail end of the arrow. Considering the variable *'Eggs'*, we know that the number of eggs existing on the farm is a function of the number of chickens. The lower-right arrow in Figure 1.1 represents the relationship that the number of *'Eggs'* found on the farm is directly impacted by the count of *'Chickens'*.

Some of the eggs have the potential of hatching into chickens. Therefore, it is also true that the count of *'Eggs'* also influences the number of *'Chickens'* on the farm. The lower-left arrow in the figure depicts this relationship.

Notice how the two relationships between *'Chickens'* and *'Eggs'* form a circular dependency. This overall dependency is known as a feedback loop. This feedback loop represents the notion that an initial change in either the number of *'Chickens'* or *'Eggs'* will eventually cause further change to the same variable. In this case there is an overall positive, or reinforcing, feedback loop for the variables *'Chickens'* and *'Eggs'*.

Now let's introduce the third variable into the discussion. There are relationships between the amount of *'Food Available per Chicken'* and the number of *'Chickens'*. Given that the farmer provides only one bucket of food for all of the chickens on a daily basis, the *'Food Available per Chicken'* is a function of the number of *'Chickens'*. If the number of *'Chickens*' were to suddenly increase, this would result in less *'Food Available per Chicken'*. The upper-right arrow notes this relationship.

Notice that the upper-right arrow includes a negative (-) symbol. This negative polarity identifies the inverse influence that the count of *'Chickens'* has on the amount of *'Food Available per Chicken'*. An inverse relationship does not specifically dictate either an increase or a decrease of a variable. In this example it would be possible for the amount of *'Food Available per Chicken'* to either increase, based on fewer chickens, or the food supply might decrease, based on a growing population of chickens. In both cases the amount of *'Food Available per Chicken'* tends to change in the opposite direction compared to the number of *'Chickens'*.

The upper-left arrow denotes that the amount of *'Food Available per Chicken'* will also influence the number of *'Chickens'* on the farm. This would be due to factors including the relative health of the chickens and their ability to obtain enough food to survive. This arrow also closes a second circular loop relationship within Figure 1.1. The overall feedback loop relationship between *'Food Available per Chicken'* and the number of *'Chickens'* is a negative, or balancing, relationship. This can be interpreted such that an initial change in one of the variables, as either an increase or a decrease, will tend to be countered and offset internally by the system. For example, an initial increase in the number of *'Chickens'* would tend to make less *'Food Available per Chicken'*. This resulting lower amount of *'Food Available per Chicken'* might eventually be severe enough to decrease the population of *'Chickens'*, thereby balancing or countering the initial increase of the chicken population.

CHAPTER 2: MODELING METHODOLOGY

2.1 Eastern Range Operations

The U.S. Eastern Range (ER) is the busiest launch range in the world. The Eastern Range, which is operated by the 45th Space Wing, is one of the two primary launch ranges under the responsibility of Air Force Space Command. The headquarters for the Eastern Range is located at Patrick Air Force Base in Florida, but the majority of ER facilities are located a few miles away at Cape Canaveral Air Force Station (CCAFS).

Through its operation of the range, the 45th Space Wing performs various key functions. These functions include:

- Commitment to provide an acceptable level of safety to the general public, launch area personnel, foreign land masses, and launch area resources; in addition to ensuring that all aspects of pre-launch and launch operations adhere to public laws and national needs

- Planning and acquisition, management of military construction programs, launch vehicle and payloads processing, launch operations, post-launch operations evaluations, and formulation of recommendations to support major program milestone decisions

- Operation, quality assurance, and oversight of space launch complexes, to provide mission assurance, resource protection, safety, and security

- Operation and maintenance of range instrumentation systems, operational planning, program support, area surveillance, air traffic control support, air traffic control radar services, range clearance, frequency management and interference control, meteorological, range safety, data collection and processing, range communications and timing, and photo/optical services

- Maintaining cooperative programs with NASA concerning all space operations at John F. Kennedy Space Center (KSC) and at Cape Canaveral Air Force Station (CCAFS) through joint program management office functions

- Operation and maintenance of a port facility in support of fleet ballistic missile programs

- Maintenance of a communications network into the east and south Atlantic areas, consisting of radio and satellite facilities in support of authorized communications customers

- Tracking capability for submarine-launched ballistic missiles, expendable launch vehicles, Space Shuttle, on-orbit satellites, and ballistic missile reentry bodies

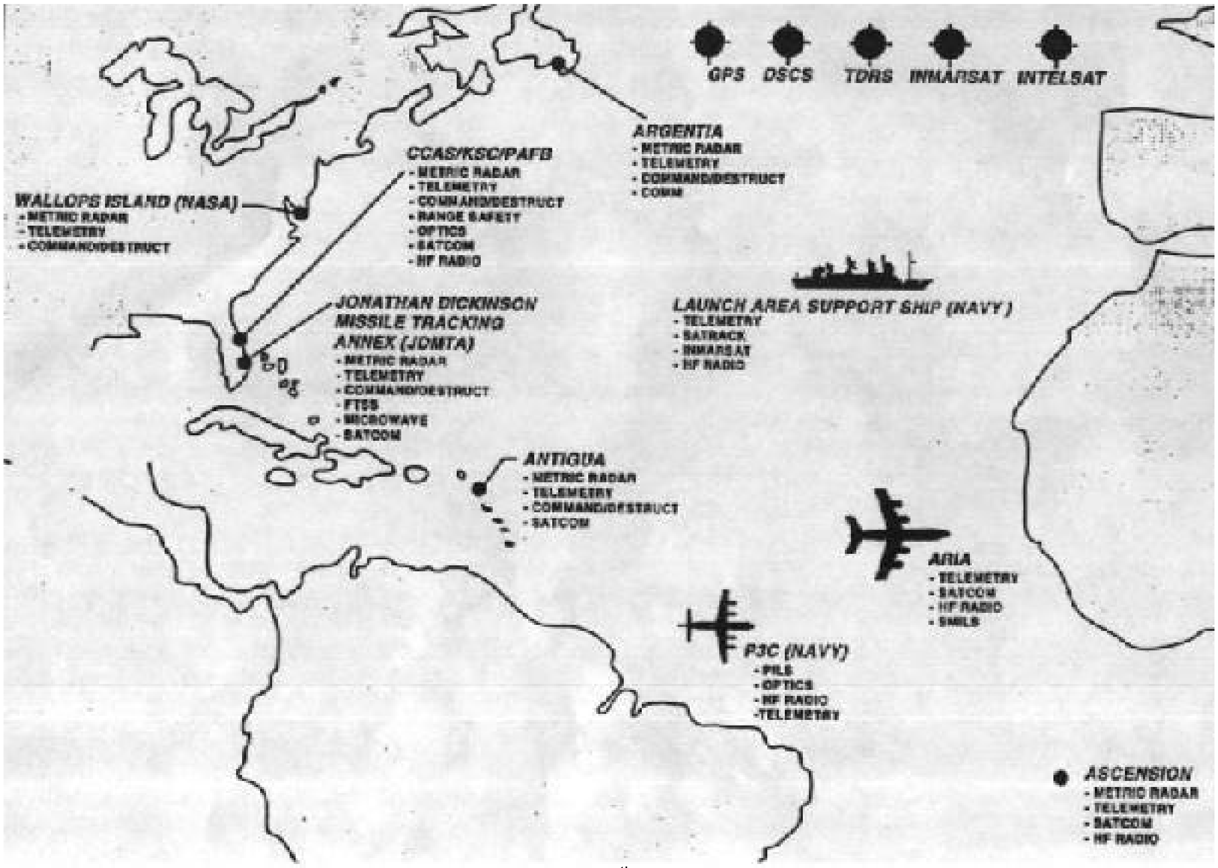
- Contract administration services per DoDD 4105.59H, Federal Acquisition Regulation

- Host base services responsibilities per AFI 25-201 or DoDD 4000.19M, Operation and Maintenance of Patrick AFB and CCAFS (USAF 1999)

The Eastern Range began as a test range for U.S. missile development programs over 50 years ago. Construction began for the first permanent launch complex at the Cape in 1950. In the following years additional launch complexes were built to support operations of MATADOR, BOMARC, SNARK and REDSTONE missile flights (USAF 2000). Through the years the primary role of the Eastern Range has shifted to support space launch efforts.

An illustration of the current Eastern Range configuration is depicted in Figure 2.1. The layout of the Eastern Range consists of instrumentation and support facilities located at the following sites:

- Patrick Air Force Base
- Cape Canaveral Air Force Station
- Port Facilities of Port Canaveral
- Jonathan Dickinson Missile Training Annex
- Florida Annexes
- Kennedy Space Center-located facilities
- Antigua Air Station
- Ascension Auxiliary Airfield
- Argentia Missile Tracking Annex

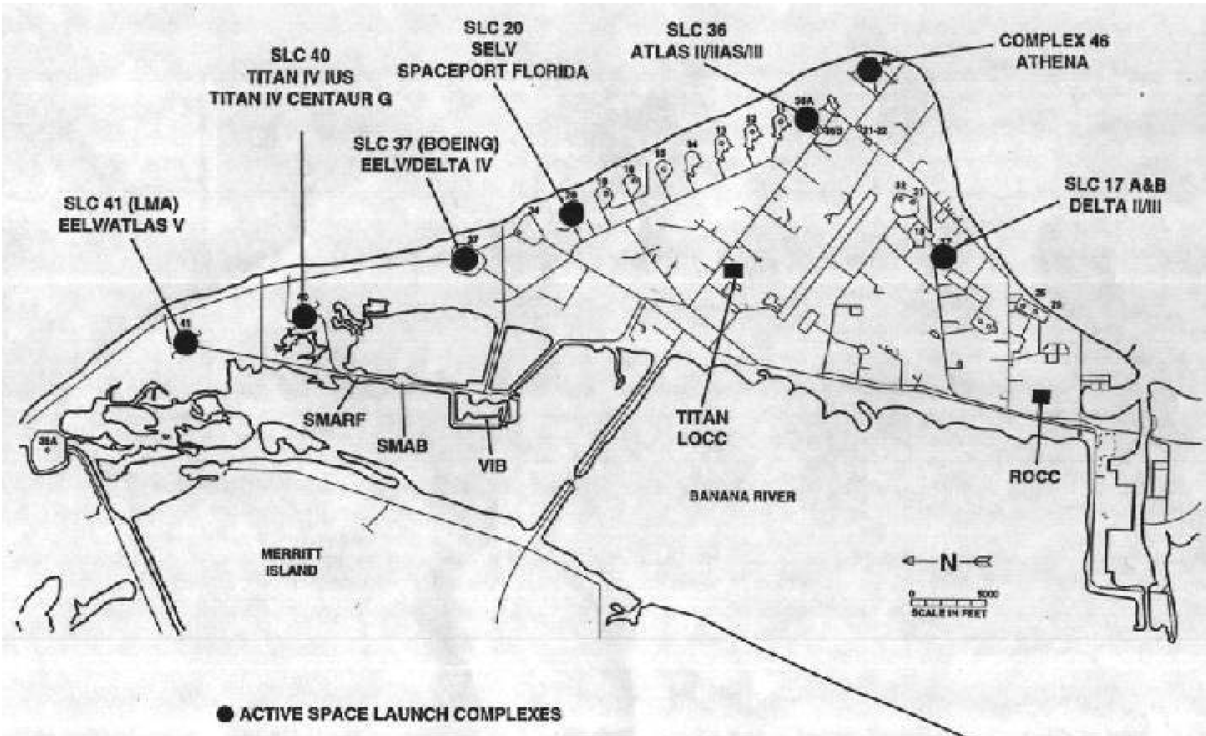


Source: 45th Space Wing 1999 Planning Guidance Document

Figure 2.1: U.S. Eastern Range (Map)

Cape Canaveral Air Force Station hosts the majority of the system components making up the Eastern Range. Figure 2.2 shows a map of the current CCAFS configuration. Cape Canaveral Air Force Station facilities include the launch complexes, vehicle and satellite assembly buildings, fuel tank farms, machine shops, testing laboratories, storage areas, utility systems, and all of the related facilities essential to support pre-launch testing and launching of aerospace vehicles. Active launch facilities include the following Space Launch Complexes (SLC):

- SLC-17A (Delta II) and 17B (Delta II, III)
- SLC-20 (Planned Spaceport Florida Authority Activities)
- SLC-37 (Planned Delta IV-EELV)
- SLC-36A (Atlas II) and 36B (Atlas II, III)
- SLC-40 (Titan IV)
- SLC-41 (Planned Atlas V-EELV)
- SLC-46 (Athena)



Source: 45th Space Wing 1999 Planning Guidance Document

Figure 2.2: Cape Canaveral Air Force Station (Map)

In addition to conducting launch operations from permanent launch pads located at CCAFS, the Eastern Range also supports the following launch activities:

- Pegasus launch vehicle activities, which are staged from a support aircraft
- Space Shuttle launches, which take place from launch pads 39A and 39B, which are located nearby at the NASA Kennedy Space Center
- Navy Submarine-Launched Ballistic Missile (SLBM) tests
- Sub-orbital rocket launches

Figure 2.3 illustrates the basic concept of Eastern Range launch operations. As previously described, there are multiple launch programs that utilize common range resources. According to specific launch vehicle processing timelines, range support is required at various points to conduct certain pre-launch and launch operations. Launch programs must request such support from the Eastern Range scheduling office. Various examples of range support include timing, command, communications, tracking, telemetry acquisition and processing, and frequency management of launch systems.

Once the range has received a request for support, the request is considered in comparison to factors such as range downtime, the range crew workload, and the necessary maintenance of critical range support systems. If the request for support from the launch program can be readily fulfilled, then the operation is scheduled and support is allocated. If however, support cannot be granted as requested, then the range may suggest an alternative option and the deconfliction process continues in search of an acceptable answer.

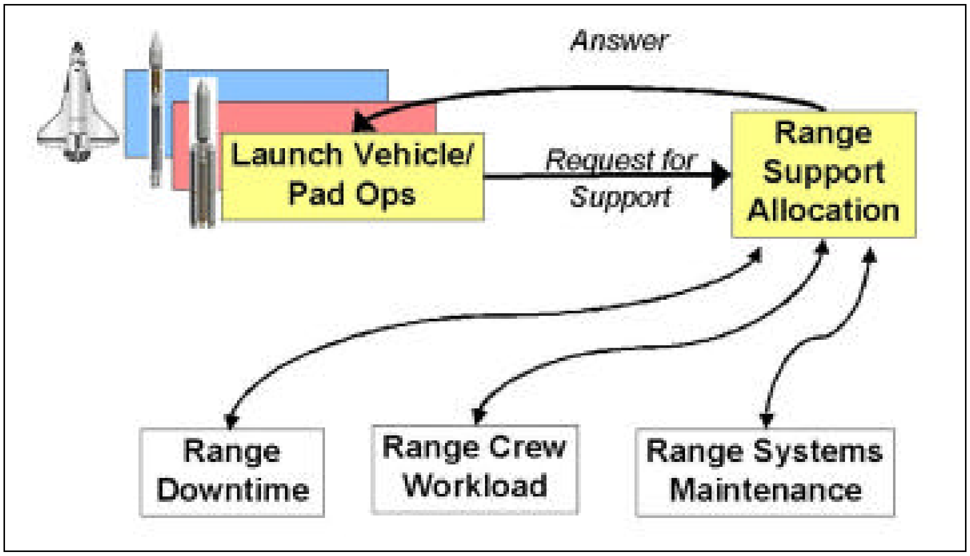


Figure 2.3: Concept of Eastern Range Launch Operations

Diverse mission requirements, varying degrees of process enhancement, and different underlying launch vehicle technologies result in unique range support requirements for each of the launch vehicle programs operating from the Eastern Range. Figure 2.4 shows the aggregate durations of range support time, necessary for each launch campaign, for most of the launch vehicle programs currently operating at the Eastern Range. The duration of range support has been classified into one of four support categories. The category of *Launch Support* refers to the amount of range systems time necessary to conduct the actual launch event in addition to the minus and plus counts. The category label *F-1 Range Reconfiguration* corresponds to a series of calibration, test, and system configuration activities that the range must perform in order to prepare for a launch. *Major Program Tests* and *Minor Operations* are prelaunch operations conducted by the launch program that require various degrees of range support as defined per specific operations directives.

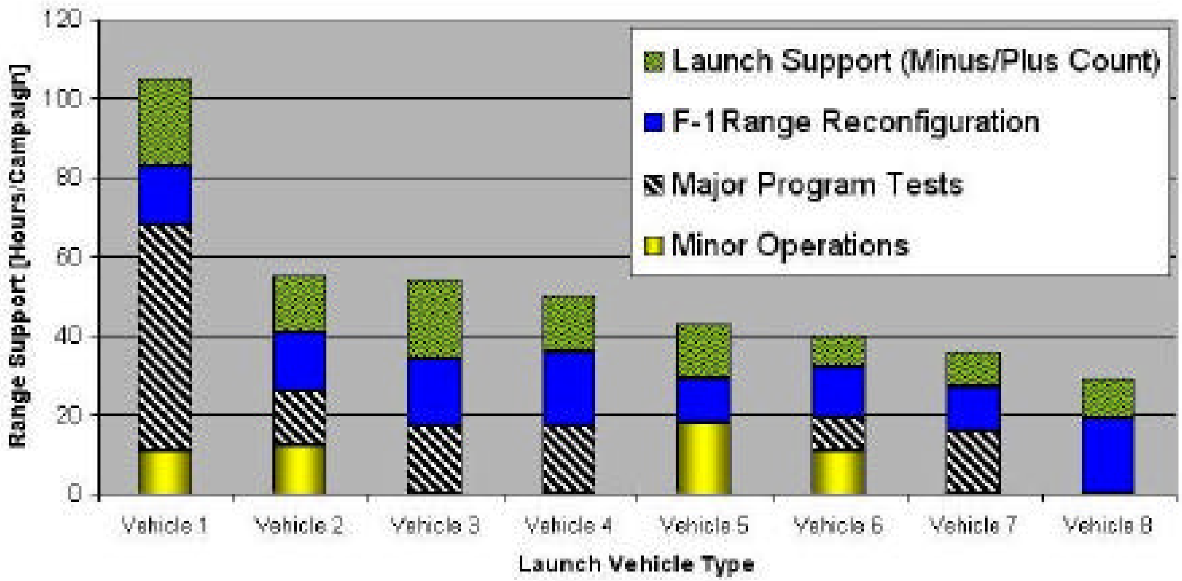


Figure 2.4: Eastern Range Launch Vehicle Support Durations

2.2 Organization of the Model

The system dynamics model, developed through the author's enhancement effort of the existing Air Force spreadsheet modeling approach, fundamentally changed the manner in which range capacity and launch operations are modeled. Rather than producing a single value of range capacity as a discrete year-end value, the system dynamics approach truly simulates events as they unfold at different points during the course of a simulated year. Instead of assuming a constant linear behavior, range operations have been modeled in a way that reflects the interdependent, dynamic, and highly non-linear nature of their "behavior".

NOTE: Any use of the words "the model" shall refer to the system dynamics model created by the author unless specifically stated otherwise.

The model has been configured to simulate Eastern Range launch operations for a specified single year period. During the course of a simulation, the model is defaulted to account for events and calculate values on an hour-by-hour basis. For each simulated hour of the year, the model performs the following series of six tasks:

1. Determines the current time
2. Checks range status for operations restrictions
3. Calculates the need for range crew rest
4. Accounts for rescheduling effects
5. Performs range systems maintenance as necessary
6. Prioritizes and allocates range support for launch operations

First, the model determines the current time of the year. This includes calculating the hour, week, month, and other convenient measures of time. Second, the model checks whether or not there are any on-going or imminent restrictions that would prevent launch operations from occurring. Examples of such restrictions would include a continuing launch operation, planned downtime, and significant maintenance. Third, the need for range crew rest is calculated based on crew workload levels. Fourth, the effects of range support rescheduling are accounted for. Fifth, range systems maintenance is performed. And finally, the model compiles a list of the launch programs that require immediate range support. Then it prioritizes the list of range support requests and appropriately allocates support in the form of time, representing the use of range resources.

The model has been organized into various sections. A visual map of the model layout is presented in Figure 2.5. Each of the seven sections performs tasks and calculations related to the name of the section. Every section is discussed in greater detail in subsequent parts of this thesis. These sections have been classified as containing variables and relationships related to the topics of:

- Time
- Restricted Periods
- Launch Vehicle Operations
- Range Crew
- Range Systems Maintenance
- Scheduling and
- Range Statistics

The blocks in Figure 2.5 represent the number of *views* associated with each section of the model. A view is simply the portion of a causal loop diagram(s) contained within a single computer screen. In other words, the number of blocks shown in the diagram approximates the number of computer screens dedicated to that section of the model. The blocks that are lightly shaded symbolize causal loop diagrams that have been recreated and amended for every launch pad in the model. Since there are currently 14 launch pads within the model, each shaded box actually represents 14 similar views. In its entirety, the model contains approximately 165 separate views.

Model Complexity

The current version of the system dynamics model accommodates up to 14 simultaneous launch flows (i.e. launch pads). While the model contains 54,610 total unique variables, there are a total of 2,536 unique visible variables that are readily apparent within all of the 165 views of the model. The difference between these two counts results from the use of array programming and subscripted variables. The model was run using a dual Pentium III, 700Mhz, 512Mb RAM PC workstation. The average time to simulate a single year, hour by hour, was approximately 5 minutes. During such a simulation, the model generates roughly 480 million explicit values, one of which is the annual Eastern Range launch capacity.

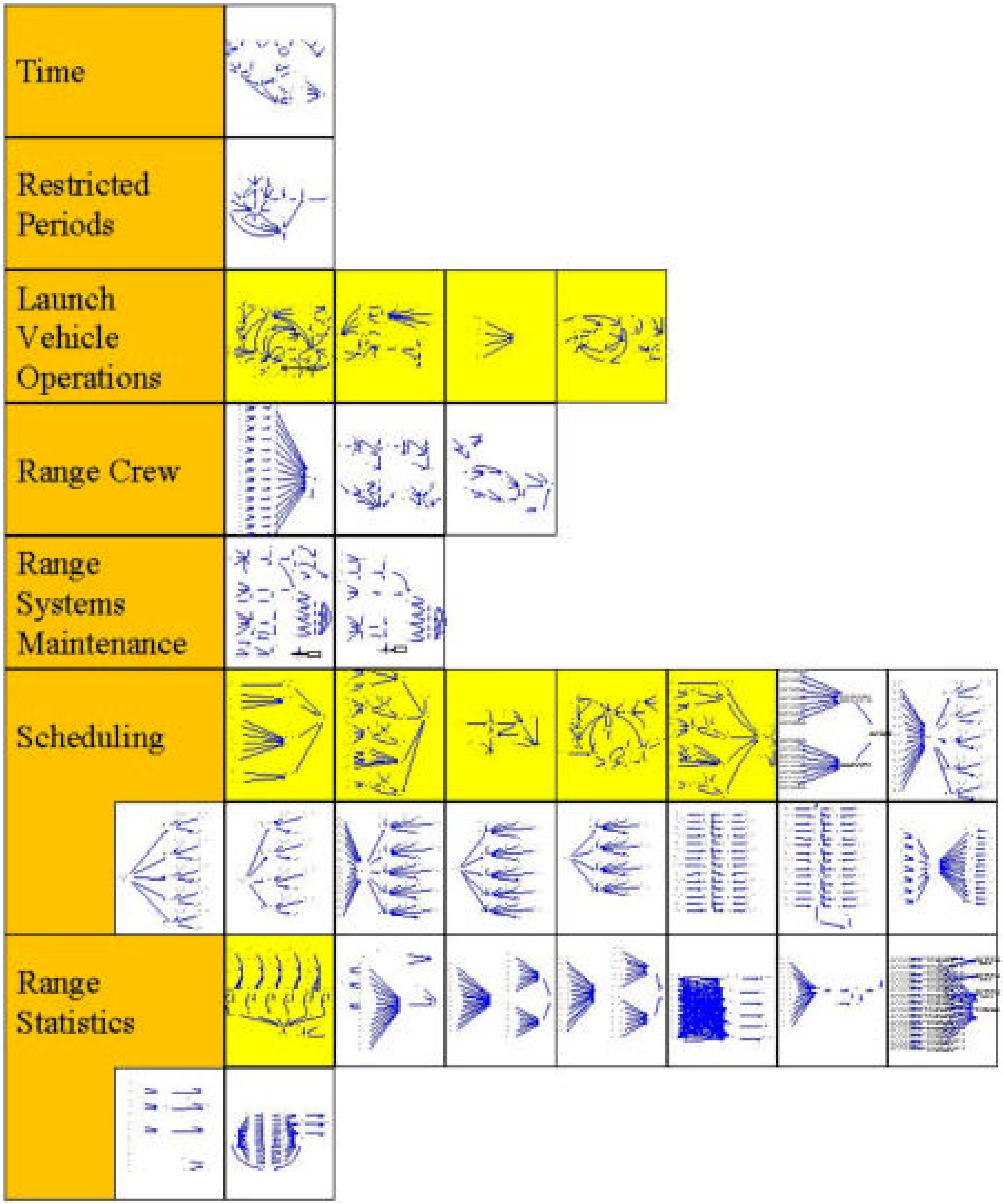


Figure 2.5: Model Layout

2.3 Time

Time is a basic, yet essential, variable for any system dynamics model. It can be represented in various units of measure and is often applied in relating one variable to another. It is necessary to give careful consideration to this dimension early on in the development of a system dynamics model due to the dependent nature of other variables.

The model is fundamentally based upon the decision to simulate events during the course of a year on an hour-by-hour basis. Pursuing this specific approach was the result of a number of factors including:

- Time fidelity of available data
- Launch forecast considerations
- Operation cycles
- Resulting model complexity and computing requirements

One important realization when using system dynamics is that time is represented as a discrete function of incremented periods. The smallest possible increment of time within a model is called a **Time Step**. Therefore the model approximates an infinitesimal point in time as a finite duration, equal in length to a single time step. Thus caution must be exercised when choosing an appropriate time step so as to not produce erroneous results with the model.

2.3.1 Description of Primary Model Structure

Figure 2.6 shows the basic model structure used to establish different measurements of time. This section of the model is generic and could even be used for other modeling efforts not related to range launch operations. Several variables, such as the following, have been highlighted within the view in order to provide the user with a quick representation of its functionality: *'Current Hour of the Day'*, *'Hours Remaining in Calendar Day'*, and *'Current Day of the Week'*.

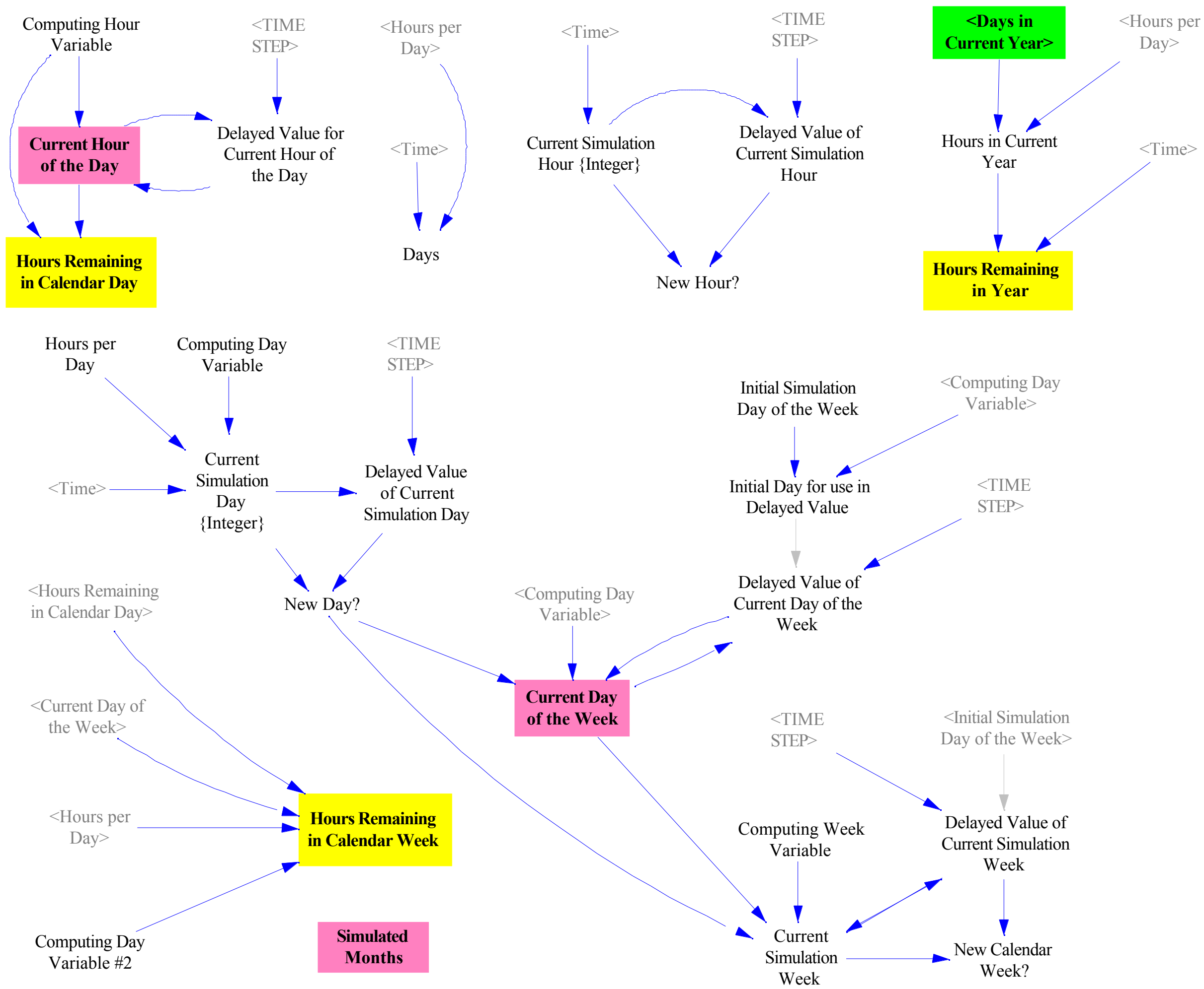


Figure 2.6: Time (Model Structure)

2.3.2 Model Inputs and Exogenous Variables

The principal inputs to this section include the following variables, which are directly dependent upon values supplied by a model user; thus their root causes are not explicitly addressed by existing model relationships:

'Days in Current Year' -(Units: Days)
Description: number of calendar days within the current year

2.4 Restricted Periods

Throughout the course of a year the Eastern Range is unavailable at certain times to support launch-related operations due to preplanned events. These restricted periods may result from either personnel factors or the limitations of range support systems. The following are some typical examples of restricting events:

- Holidays
- Training exercises
- Upgrading of range systems

This section of the model randomly assigns restricted dates based on an annual number of restricted days specified by a user.

2.4.1 Description of Primary Model Structure

The section of the model responsible for assigning restricted range periods is depicted in Figure 2.7. The modeling approach used to achieve this function can be understood by examining those variables represented in bold text with shaded backgrounds.

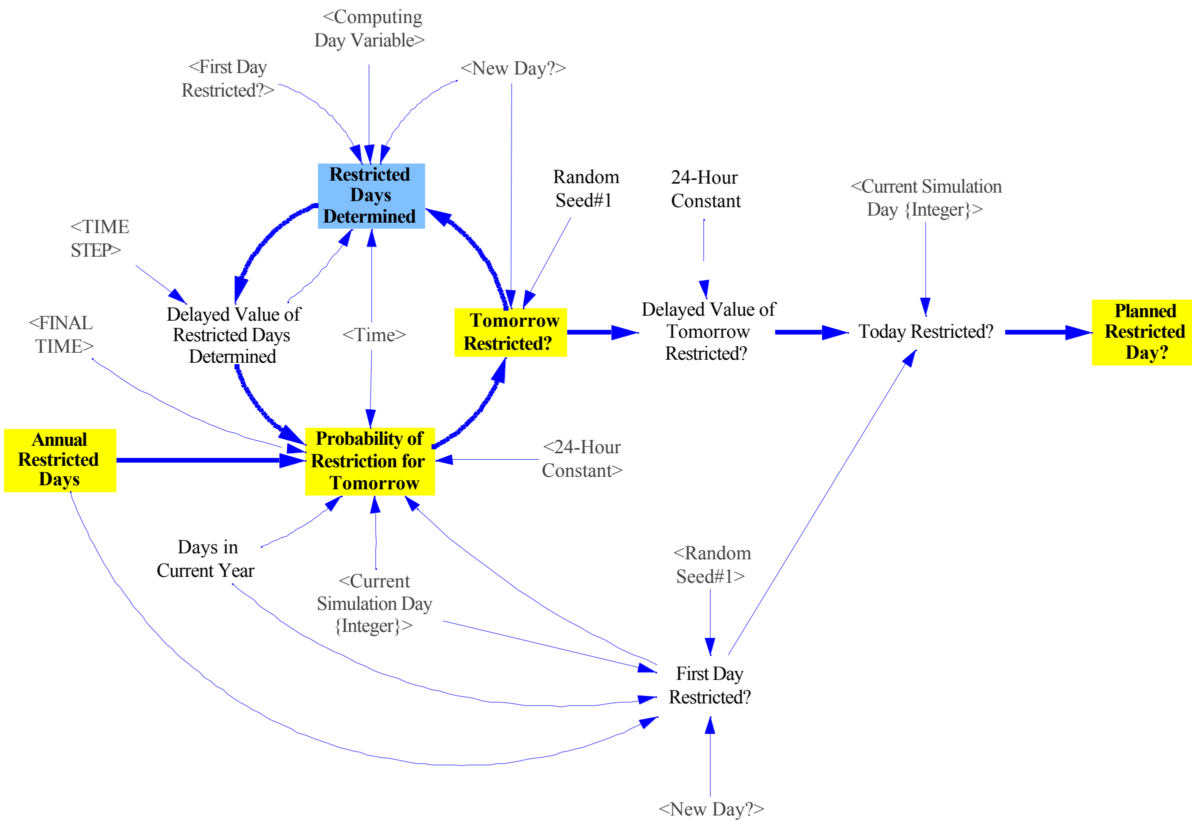


Figure 2.7: Planned Restricted Periods (Model Structure)

The variable called *'Annual Restricted Days'* can be found on the left-hand side of the figure and is simply the annual amount of restricted range time, as chosen by a user. From this value the *'Probability of Restriction for Tomorrow'* can be calculated with the aid of some supplementary time information. Determination of whether tomorrow will be restricted (*'Tomorrow Restricted?'*) is subsequently accomplished by applying this probability to a random function. From this point, two paths of further dependence are discussed:

1) Based on whether tomorrow is restricted or not, the annual count of restricted days already determined (*'Restricted Days Determined'*) is adjusted accordingly. This value in turn is used to recalculate the *'Probability of Restriction for Tomorrow'* during the next iteration. Note the feedback loop involving the variables *'Probability of Restriction for Tomorrow'*, *'Tomorrow Restricted?'*, and *'Restricted Days Determined'*.

2) A second path relies on the value of *'Tomorrow Restricted?'* to eventually determine if the current day is a *'Planned Restricted Day?'*.

2.4.2 Model Inputs and Exogenous Variables

The principal inputs to this section include the following variables, which are directly dependent upon values supplied by a model user; thus their root causes are not explicitly addressed by existing model relationships:

'Annual Restricted Days' -(Units: Days)
Description: user-defined number of restricted days for the current year

2.5 Launch Vehicle Operations

The timeline of activity for a single mission at a launch facility is referred to as a **launch flow**. The sequence of events for a given launch campaign is comprised of both operations requiring range support and periods of time not requiring the utilization of common range resources. Some examples of range support include the timing, tracking, communications, command, and telemetry functions necessary to conduct specific launch operations.

Depicted in Figure 2.8 is an example launch flow for a typical launch campaign. The figure should be read from left to right as time progresses and events occur. The represented launch facility (an example launch pad) has the capability to conduct a nominal launch campaign every 47 calendar days. This length of time, from one launch to the next at a single facility, is referred to as a **launch span**.

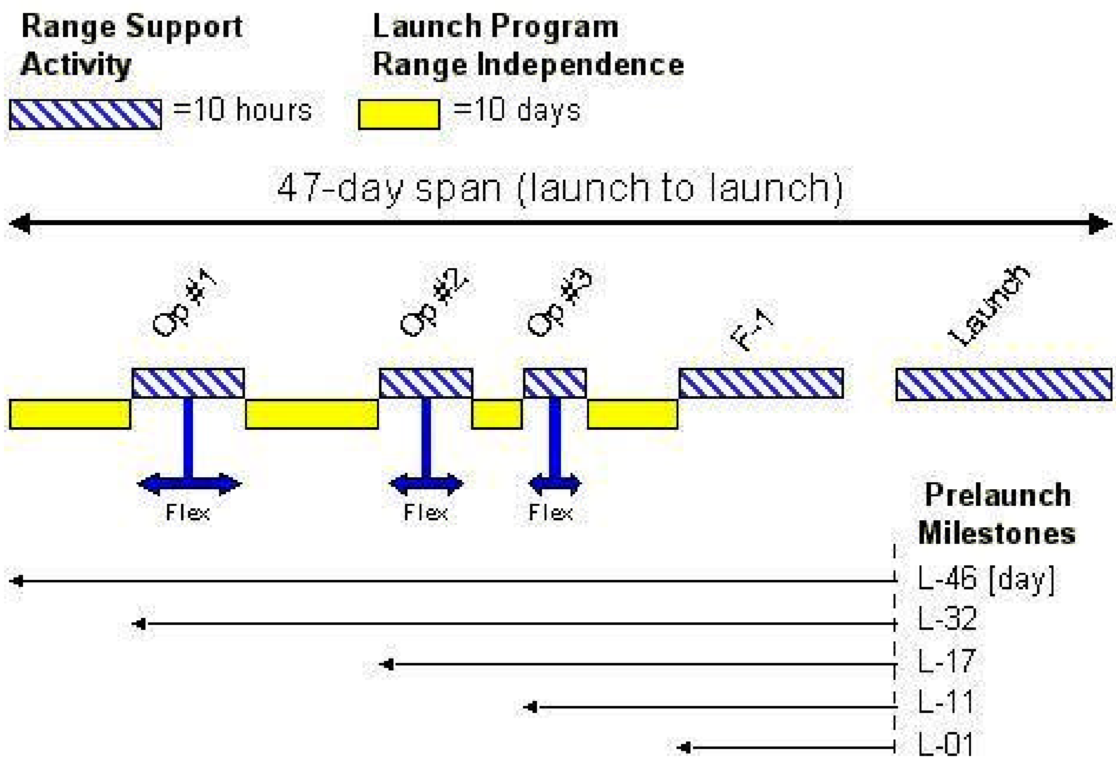


Figure 2.8: Launch Flow

The launch flow shown in the diagram includes three sequential operations, which require range support and are displayed as crosshatched boxes. The length of each box, as shown in the legend at the top of the figure, represents the duration of range support necessary to conduct each activity. The F-1 activity is an operation undertaken by the range to reconfigure the range systems in order to conduct the actual launch day event. The final operation of a typical launch flow is the launch.

The interim periods between the depicted operations requiring range support consist of additional tests and activities. These other types of operations are performed independent from range support and are depicted as solid shaded bars. Note that the lengths of the bars representing the range independent activity periods are relative to a different scale as shown in the legend of Figure 2.8.

For a typical launch campaign, the commencement of important events in the launch flow, such as a wet dress rehearsal, is measured back in time from the projected day of launch. These prelaunch milestones are tracked in terms of negative days from the launch and can be seen at the bottom of Figure 2.8.

The specific dates suggested within the diagram correspond to nominal values for this example launch program. In reality, some of the operations could be conducted at slightly different times without any impact to the launch date. The capability of a launch program to conduct a specific prelaunch operation at any one of multiple opportunities, due to the ability to work other tasks in parallel, is referred to as **operation flexibility**. The word "Flex" and a two-way arrow depict this concept of operational flexibility for some of the operations represented in Figure 2.8.

2.5.1 Description of Primary Model Structure

This section describes the approach used to model a launch flow for a generic launch program called "Program 1." The system dynamics model has been configured to account for up to 14 launch programs. The model structure associated with the remaining 13 launch programs is not presented in its entirety due to its identical nature to the model structure presented herein. The term "launch program" is used within the context of this thesis as a capability to conduct a launch vehicle campaign. An analogy can be made between a "launch program" and a launch pad[2].

A part of the model structure associated with launch vehicle operations is depicted in Figure 2.9. Near the top and central part of the figure is the variable *'Program1 Op Type'*. This variable classifies each identified operation of a launch flow. It takes on one of three possible values corresponding to a specific operation type defined as 1: major op, 2: minor op, 0: minimum interim.

- **Major operation**- a launch campaign related operation requiring significant range support resources; therefore the range can only support one major operation at a time
- **Minor operation**- a launch campaign related operation requiring a lower amount of range support resources; therefore the range can support simultaneous minor operations or even possibly minor operations during a major operation
- **Minimum interim**- a period of time during which no major or minor operations are conducted, although other operations not requiring range support may be performed

When the launch program is prepared to conduct an operation, the model generates a request for range support (*'Program1 Op Request for Support'*) based on the operation type (*'Program1 Op Type'*) and the duration of support required (*'Program1 Op Duration'*). This request is submitted to the range and the launch program is either issued a "Go Ahead" (*'Program1 Go Ahead'*) or must wait until support is granted.

If multiple launch programs are requesting range support simultaneously, then the range may take into consideration the length of time that a launch program has been waiting to receive range support (*'Program1 Request Wait Time'*). For a more detailed explanation of the range scheduling and support allocation process see thesis section 2.8.

[2] The Pegasus launch vehicle program and the U.S. Navy Submarine Launched Ballistic Missile (SLBM) program do not use launch pads, but are also considered as launch programs.

Once support has been granted, the operation will then be conducted (*'Program1 Op Activeness'*) through completion (*'Program1 Op is Finished'*). A model simplification has been made such that once an operation has begun, it will continue successfully until it is completed.

As an operation is completed the next operation of a launch flow will thereby have its prerequisites accomplished, which is noted by the variable *'Program1 Op Prerequisites Completed'*. This sets the stage to begin the loop once again by requesting range support for the new operation.

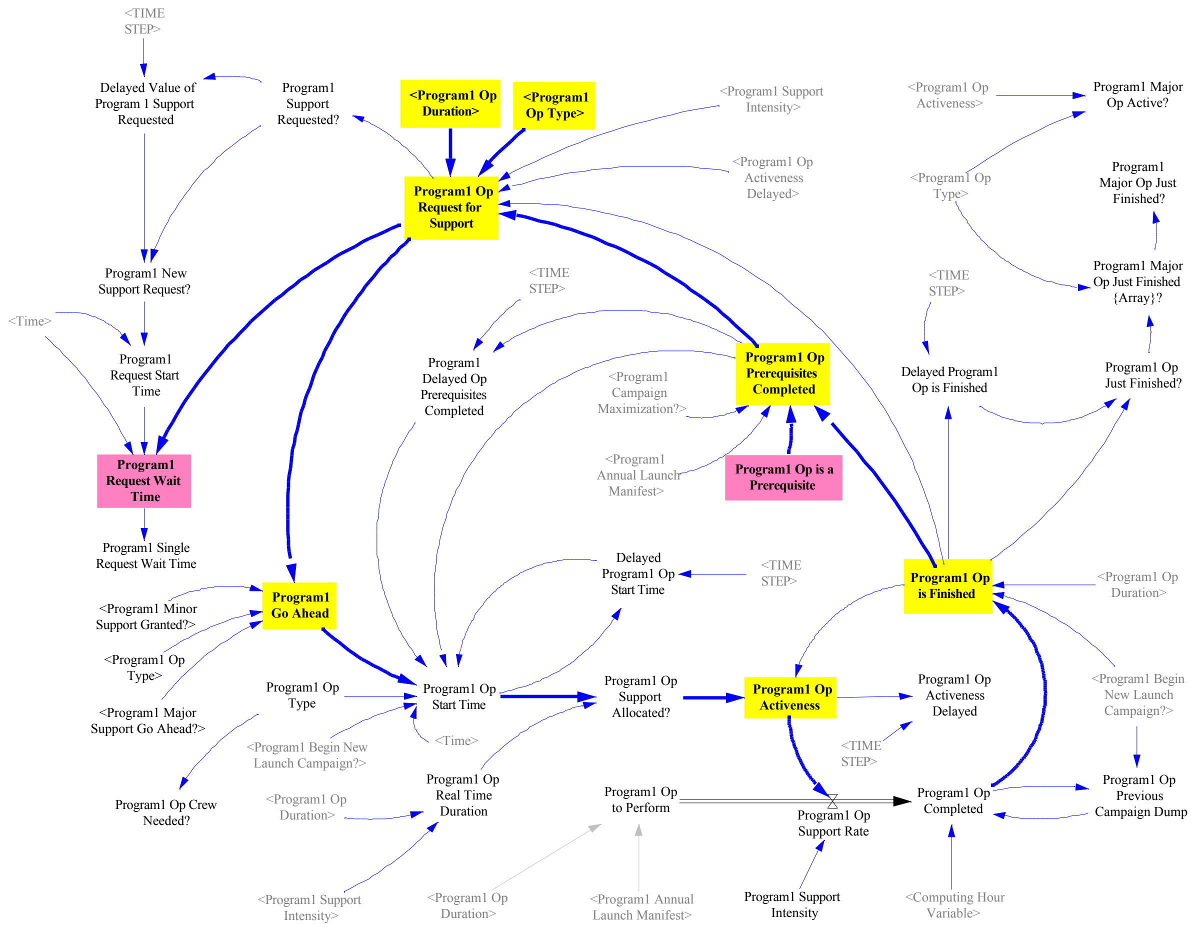


Figure 2.9: Launch Vehicle Operations (Model Structure 1)

The concept of operation flexibility is modeled through the structure presented in Figure 2.10. The variable *'Program1 Op Baseline Duration'* contains an array of user-specified values representing the duration of each operation, if each operation was to begin at the earliest possible start time for the current launch campaign. *'Program1 Op Flexibility'* represents the maximum amount of time the commencement of an operation may be delayed without affecting the length of the total launch span, and therefore the launch date. The model uses these two variables in conjunction with the *'Program1 Request Wait Time'* to determine the actual amount of time devoted to each operation or interim period. These actual durations are captured in the variable array labeled *'Program1 Op Duration'*.

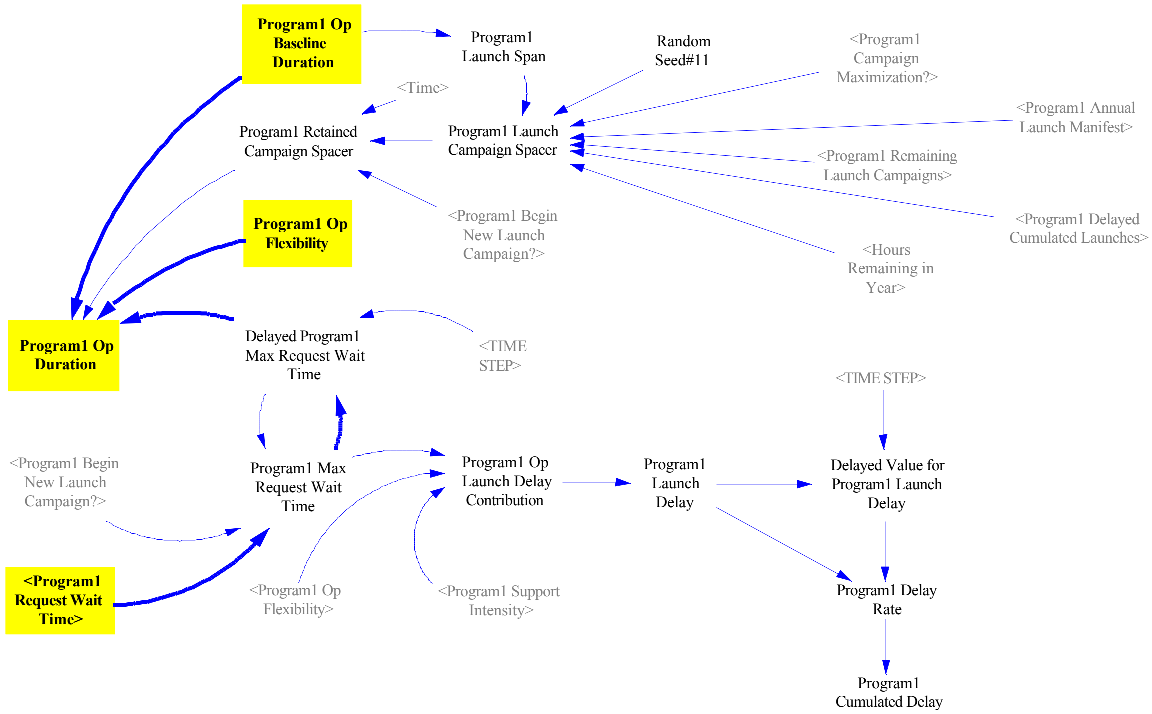


Figure 2.10: Launch Vehicle Operations (Model Structure 2- Op Flexibility)

The model structure depicted in Figure 2.11 is devoted to a phenomenon called **Inflation of Minor Operations**. This occurs when an operation is standardized as a minor operation, but for a specific mission additional range support is required beyond the standard amount to the level that it has an impact on range availability similar to that of a major operation.

The model assigns random minor operations as being inflated (*'Program1 Minor Op Inflation?'*) based on the *'Program1 Minor Op Inflation Probability'* specified by a model user.

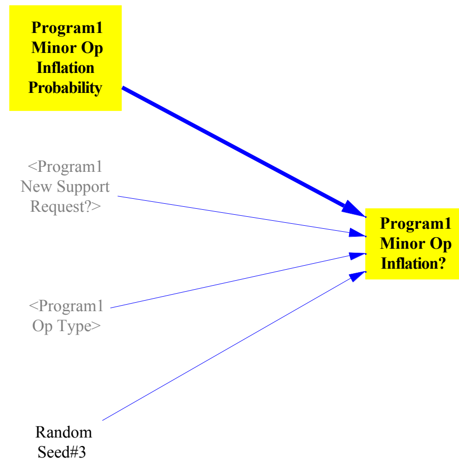


Figure 2.11: Launch Vehicle Operations (Model Structure 3- Minor Op Inflation)

Figure 2.12 shows the section of the model responsible for keeping track of the current launch program campaign and annual launch manifest. The variable *'Program1 Annual Launch Manifest'*, a user-specified variable, which can be found near the center of the figure, denotes the number of Program1 launches expected to occur during the current year. As Program1 launches occur during the course of a simulation, they are counted by the variable *'Program1 Cumulated Launches'*. The variable *'Program1 Launch Campaign'* simply retains the current launch campaign number for the launch program.

Every launch program is also assigned a unique identification number (*'Program1 Unique Pad Identity'*) to be used for internal computer modeling purposes. Once the range crew has completed the F-1 range reconfiguration activity in preparation for a launch, the range enters into a period referred to as **Range Lockdown**. During range lockdown the only program that may receive range support for a major operation is the program for which the range has been reconfigured for launch. Using the variable array *'Program1 Op is Finished'*, the model can determine whether a state of range lockdown exists due to a given launch program (*'Program1 Range Lockdown?'*).

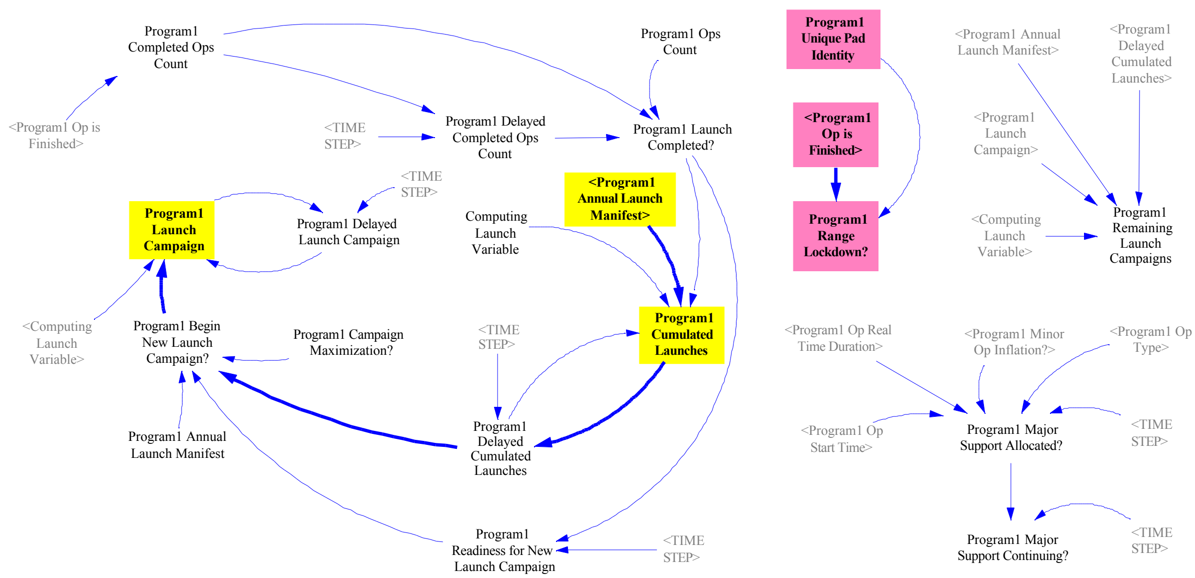


Figure 2.12: Launch Vehicle Operations (Model Structure 4- Launch Campaign)

2.5.2 Model Inputs and Exogenous Variables

The principal inputs to this section include the following variables, which are directly dependent upon values supplied by a model user; thus their root causes are not explicitly addressed by existing model relationships:

'Program1 Op Type' -(Units: Dmnl)
Description: operation type defined as 1:major op, 2:minor op, 0:minimum interim

'Program1 Op is a Prerequisite' -(Units: Dmnl)
Description: array of program operations with designations for prerequisites

'Program1 Op Baseline Duration' -(Units: RangeHours)
Description: baseline duration of range support for the operation or interim period

'Program1 Op Flexibility' -(Units: RangeHours)
Description: maximum amount of time the commencement of an operation may be delayed without affecting the length of the total launch span (and therefore the launch date)

'Program1 Minor Op Inflation Probability' -(Units: Dmnl)
Description: percentage requests for minor operations support that require significant range resources, thereby having an increased impact on the availability of range support for other requests {Value must be within the range from 0 to 1}

'Program1 Annual Launch Manifest' -(Units: Launches)
Description: number of annual launches expected for this facility

'Program1 Unique Pad Identity' -(Units: Dmnl)
Description: denotes a unique number used to identify this launch facility for internal modeling purposes

2.6 Range Crew

The personnel responsible for operating the range systems, which provide range support functions such as tracking, telemetry acquisition, and command destruct, are contracted civilian employees. Computer Sciences Raytheon currently operates most of these range assets under an agreement with the U.S. Air Force called the Range Technical Services (RTS) Contract (USAF 2000). The exact number of RTS personnel required for each launch varies according to the complexity of the mission support requirements. A typical land-based launch is estimated to involve the efforts of approximately 200 members of the range crew(USAF 2000).

2.6.1 Description of Primary Model Structure

This section of the model is devoted to calculations related to range crew work times. These include determining the amount of time the crew has recently worked and also the amount of time remaining within particular periods of interest. There are three primary criteria associated with range crew work times. These criteria are outlined in the range safety requirements document *Eastern and Western Range Safety Requirements* (USAF 1997):

1. Maximum 12-hour shift, unless approved by Range Safety or USAF Squadron Commander, with at least 8 hours of rest after 12 hours of work

2. A maximum of 60 hours per week

3. A maximum of 14 consecutive days

The focus of this model section is to produce specific information related to the work time criteria previously mentioned; however, much of the evaluation associated with potential work hours due to support requests is handled in a different section of the model (see thesis section- 2.8.1.1Consideration of a Support Request). The modeling approach used to achieve this function can be understood by examining those variables represented in bold text with shaded backgrounds.

The entire range crew section has been divided into three views in order to reduce the amount of information contained on any single computer screen. A portion of each view is depicted in the following figures with the intent of representing only the primary relationships and variables within the section.

In Figure 2.13 a portion of a view is depicted. The variable *'Range Crew Activity'*, shown on the right-hand side of the figure, is the rate of operation support provided by the range crew. This value is used in the determination of crew rest periods. It is essentially a dimensionless quantity because it represents the number of hours of support provided within an hour of time.

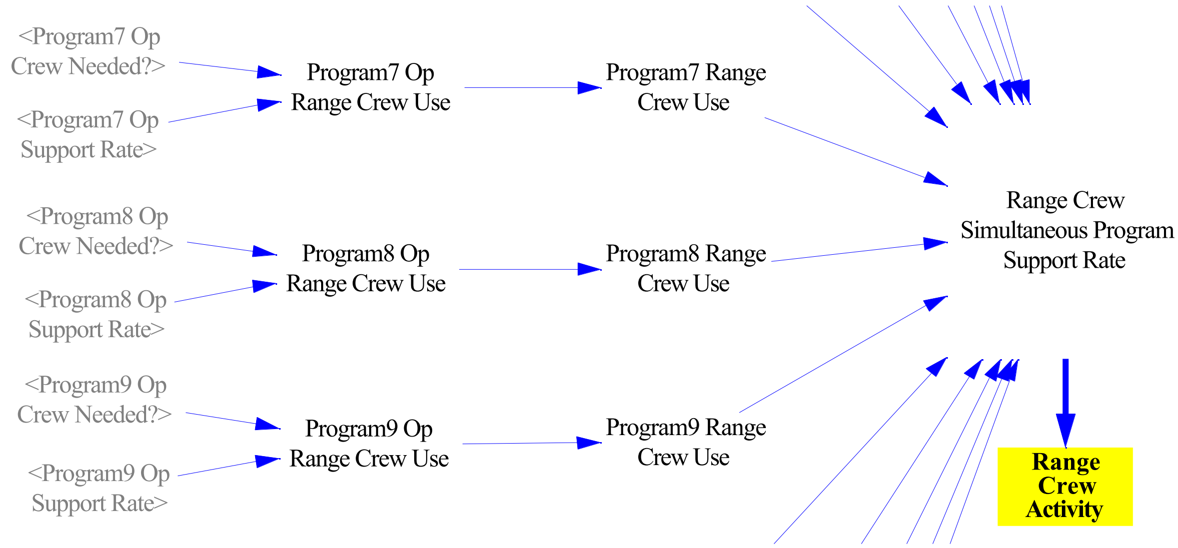


Figure 2.13: Range Crew (Model Structure 1)

Various crew workloads are tracked in this section of the model such as the *'Range Crew Calendar Week Workload'* and the number of *'Continuous Days Worked'* as shown in Figure 2.14. The variable *'Maximum Continuous Workdays'* takes a user-specified value and represents the maximum number of contiguous 24-hour blocks during which the crew is allowed to work. Using the values of *'Maximum Continuous Workdays'* and *'Continuous Days Worked'*, the *'Time Remaining Until Continuous Workdays Limit'* can be determined.

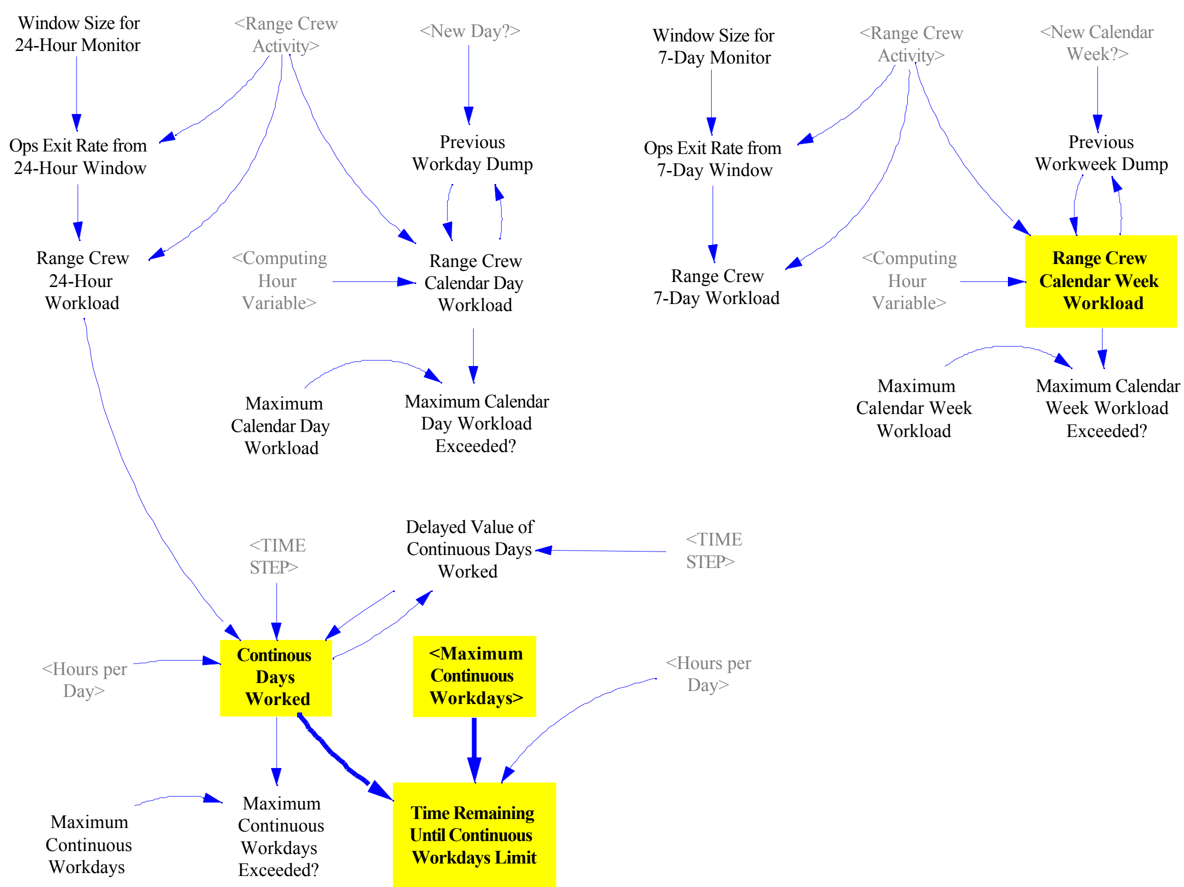


Figure 2.14: Range Crew (Model Structure 2)

Figure 2.15 depicts the third view of this model section. The variable *'Crew Activity?'* simply describes whether the crew is currently working and is found on the left side of Figure 2.15. The *'Minimum Nominal Rest Period'* is specified by a model user and corresponds to one of the work time criteria as described previously. These two variables in conjunction with the rate of range support (*'Range Crew Activity'*) and some other supplementary variables are used to determine the amount of time the crew has worked during the current shift (*'Range Crew#1 Cumulated Shift Workload'*). The *'Maximum Nominal Shift Duration'* is also specified by a model user and corresponds to one of the work time criteria. It is used along with the *'Range Crew#1 Cumulated Shift Workload'* to calculate the amount of time remaining within the current shift of work (*'Maximum Remaining Hours in a Continuing Nominal Shift'*).

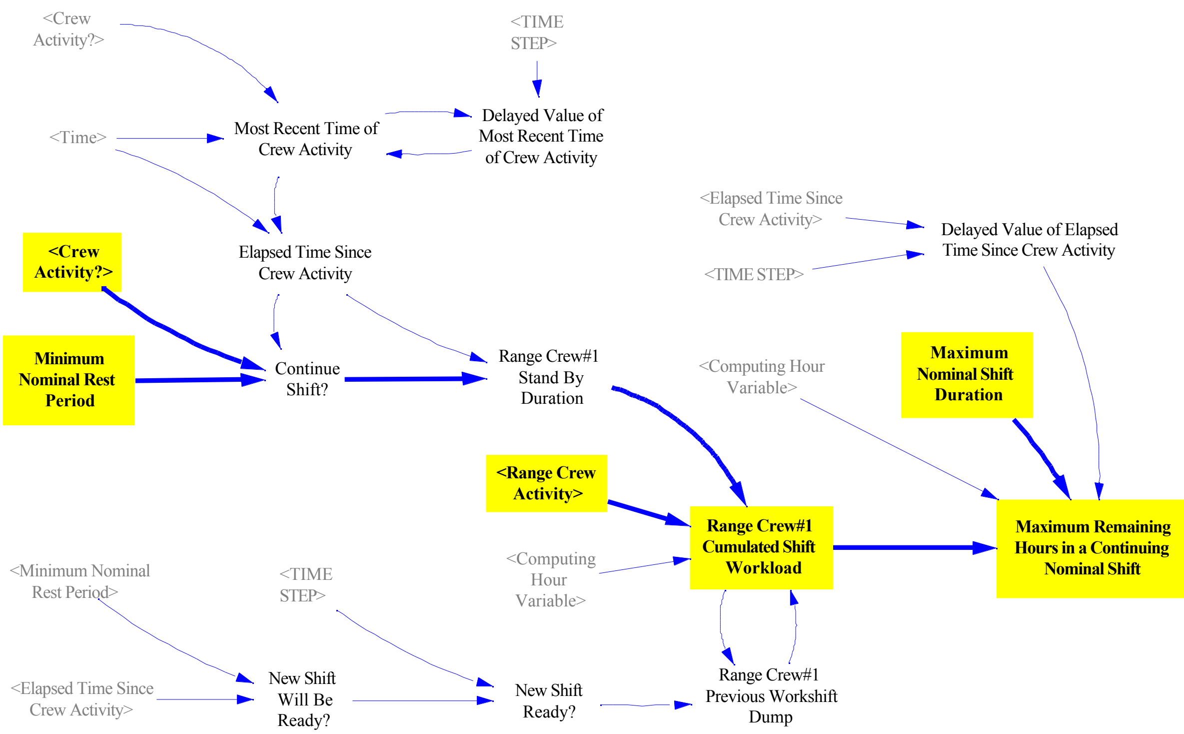


Figure 2.15: Range Crew (Model Structure 3)

2.6.2 Model Inputs and Exogenous Variables

The principal inputs to this section include the following variables, which are directly dependent upon values supplied by a model user; thus their root causes are not explicitly addressed by existing model relationships:

'Maximum Continuous Workdays' -(Units: Days)
Description: maximum number of contiguous 24-hour blocks during which the crew is allowed to work

'Minimum Nominal Rest Period' -(Units: Hours)
Description: minimum duration of rest allotted to a crew between consecutive shifts of work

'Maximum Nominal Shift Duration' -(Units: Hours)
Description: maximum allowed duration of a crew work shift under nominal circumstances

2.7 Range Systems Maintenance

Range systems include the instrumentation, network, control, and display segments required to support range activities. Although the primary mission of the Eastern Range is to support spacelift operations, secondary missions exist such as the Multiple Object Tracking Radar (USAF 1999). Maintenance of these systems occurs on both a planned and unplanned basis. Most planned maintenance is performed between launch operations, as preventative maintenance, with the intentions of having minimal impact to range support availability. On the other hand, unplanned maintenance becomes necessary at times, usually in response to an event, to repair those systems that are not functioning properly.

2.7.1 Description of Primary Model Structure

This section of the model accounts for unplanned maintenance of the range systems. Although an argument can be made for performing a more detailed analysis with the inclusion of planned maintenance activities, it is worthwhile to emphasize that the intent of this research is more focused on assessing the feasibility of system dynamics as a modeling platform for range launch operations. With this consideration in mind a decision was made to capture the type of systems maintenance with the highest perceived impact to launch operations, that being the unplanned maintenance.

For the purposes of modeling, unplanned maintenance is classified into the following two categories according to when the maintenance becomes necessary:

- **Fixed Maintenance** refers to maintenance performed in response to a need for a system repair during a period not associated with launch-related operations. This maintenance may have been prompted by such causes as a weather event, non-spacelift operation, or even aging of equipment.
- **Variable Maintenance** refers to maintenance performed in response to a need for a system repair during a launch-related operation.

2.7.1.1 Fixed Maintenance

The impact of fixed maintenance is modeled in part through the relationships illustrated in Figure 2.16. This section of the model is driven by a user-specified value for the cumulated *'Annual Fixed Maintenance Time'*. The model is programmed to generate fixed maintenance activity at a self-adjusting probabilistic rate based on the amount of *'Fixed Maintenance Time Already Allocated'*. A single simulation of the model, emulating one year, will ultimately conduct a cumulated amount of *'Annual Fixed Maintenance Time'*.

In reality, the duration of each maintenance task will vary according to the extent of the problem and the ability of the maintenance personnel to address it. Some issues can be corrected in a short amount of time directly by the range crew, but other situations may require the intervention of maintenance personnel and may last for an extended period of time. To reflect such complexity, the duration of each fixed maintenance activity was classified into one of five categories contained within the variable array called *'Fixed Maintenance Category Duration'*. These categories have been set at increments of 4, 8, 24, 48, and 72 calendar hours to account for various levels of necessary fixed maintenance.

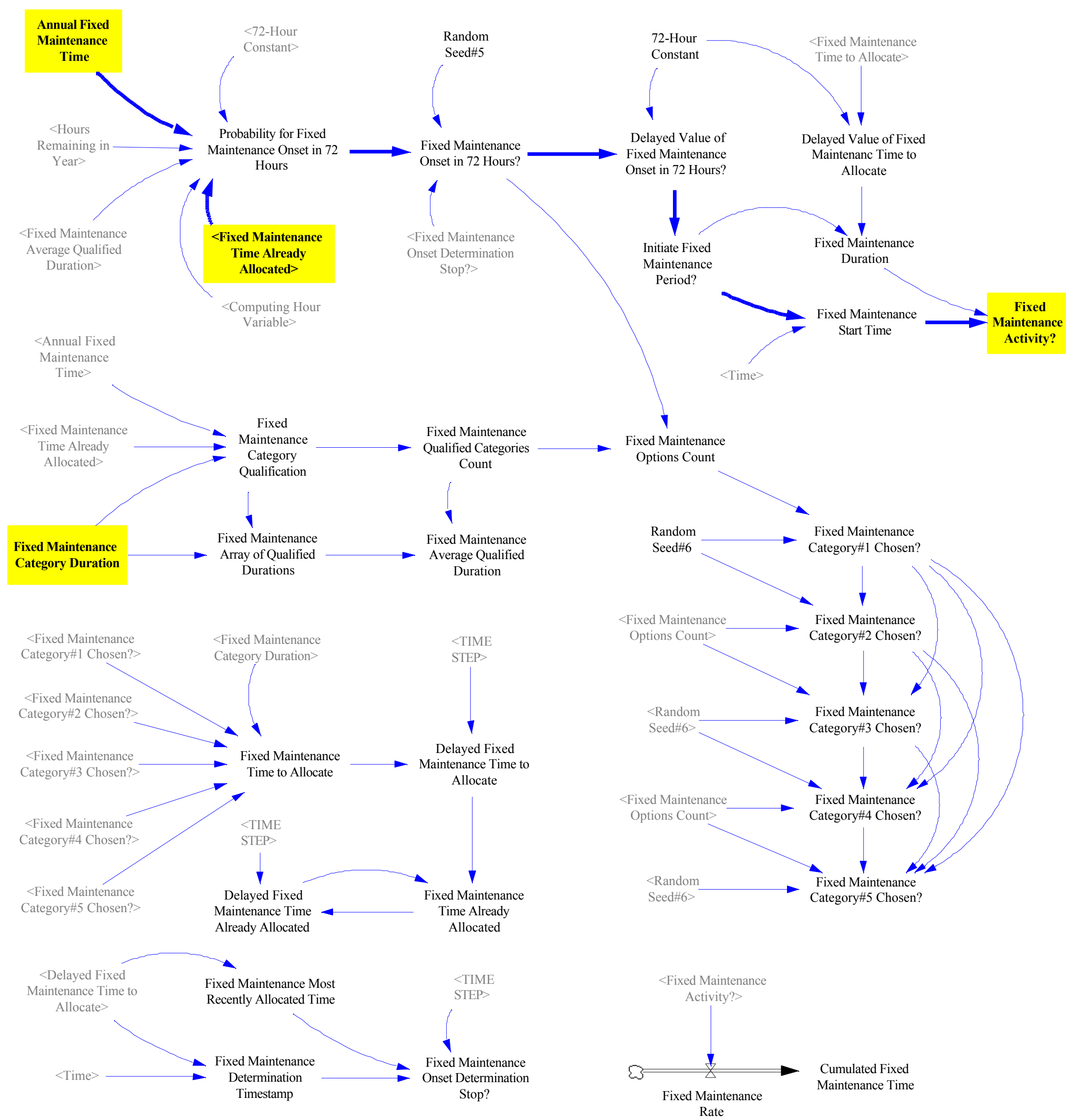


Figure 2.16: Range Systems Maintenance (Model Structure 1- Fixed Maintenance)

2.7.1.2 Variable Maintenance

In actuality, variable maintenance is carried out as a result of both major and minor operations. A simplified modeling assumption was made such that variable maintenance will only be performed upon the completion of a major operation. This was determined to be a justified approach, given that the maintenance-related data furnished to the researcher was already aggregated to a level of maintenance time on a per nominal launch basis and that each launch campaign requires at least two major operations[3].

Figure 2.17 presents the dependence of variables used to model the application of variable maintenance. This section of the model is based on the premise that there is a direct relationship between the extent the range systems are used and the necessary amount of maintenance time resulting from that use. This section is driven by a user-specified value called the *'Variable Maintenance Ratio'*, which represents the nominal rate at which variable maintenance should be applied based on the amount of range systems use. The modeling approach is a variation of that used to model the fixed maintenance time, but it also makes use of a self-adjusting probabilistic rate. A single simulation of the model, emulating one year, will ultimately conduct a cumulated amount of variable maintenance time proportional to the amount of range systems use.

As previously explained in the section covering fixed maintenance, the duration of each maintenance task will vary according to the extent of the problem and the ability of the maintenance personnel to address it. To reflect such complexity, the duration of each variable maintenance activity was classified into one of five categories contained within the variable array called *'Variable Maintenance Category Duration'*. These categories have been set at increments of 4, 8, 24, 48, and 72 calendar hours to account for various levels of necessary variable maintenance.

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[3] Every launch vehicle in the current manifest, including an SLBM, requires an F-1 (range reconfiguration) and launch event for each launch campaign

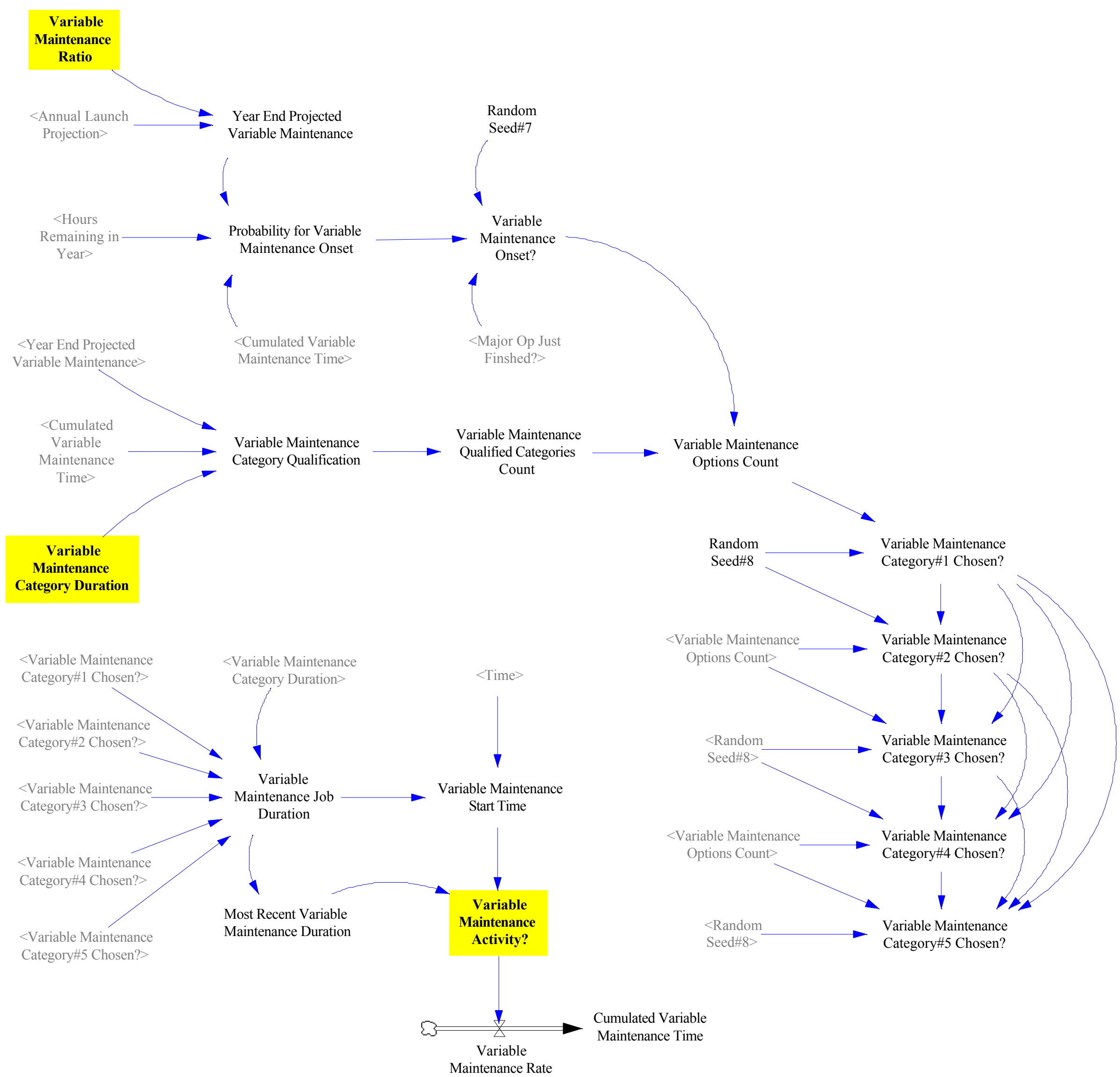

Figure 2.17: Range Systems Maintenance (Model Structure 2- Variable Maintenance)

2.7.2 Model Inputs and Exogenous Variables

The principal inputs to this section include the following variables, which are directly dependent upon values supplied by a model user; thus their root causes are not explicitly addressed by existing model relationships:

'Annual Fixed Maintenance Time' -(Units: Hours)
Description: annual maintenance time resulting from non-launch related activities

'Fixed Maintenance Category Duration' -(Units: Hours)
Description: array of possible durations necessary to perform a fixed maintenance activity

'Variable Maintenance Ratio' -(Units: Hours/Launch)
Description: value representing the ratio of annual variable maintenance hours to launches

'Variable Maintenance Category Duration' -(Units: Hours)
Description: array of possible durations necessary to perform a fixed maintenance activity

2.8 Scheduling

A generic launch scheduling timeline is depicted for the Eastern Range in Figure 2.18. The **National Launch Forecast** is a projection of U.S. launches, which extends 11 years into the future (USAF 2000). USAF Headquarters Space Command compiles this long range forecast, which is reviewed on a semi-annual basis with coordination from NASA, DoT/FAA, commercial launch contractors, and other DoD and federal agencies. The forecast corresponds with the federal budget cycle and is meant to provide a complete picture of U.S. space launch activity.

The immediate 3 years are not specifically addressed through the National Launch Forecast. Instead, a more dynamic forecast called the **Space Launch Manifest** covers the current 36 months and is approved by the Current Launch Schedule Review Board (USAF 2000).

Roughly 18 months before a planned launch, the launch dates are incorporated onto the Eastern Range **Current Launch Schedule**. For a typical mission a primary and secondary launch date will be scheduled in case of a need for a second launch attempt. During this period it is also important for the range scheduling office to consider when the F-1 range reconfiguration operation can be performed in support of the launch.

The process of initially scheduling launch dates may take several iterations before all involved interests are appeased. A circular arrow in the corresponding section of Figure 2.18 represents this idea. The policy of the Eastern Range scheduling office has been to process all launch scheduling requests with the same level of priority, regardless of which organization or range customer submits the request. In this spirit national security, civil, and commercial missions have historically received an equivalent amount of scheduling consideration and were assigned launch dates primarily based upon the date each request was submitted (USAF 1996).

At some point *no later than* 30 days before launch, all remaining major operations, which require range support, must be scheduled with the range. The specific support requirements for each launch campaign are handled through the Universal Documentation System.

During the 30-day period leading up to a launch, all remaining operations must be conducted. If the first launch attempt is aborted, and therefore the program does not enter into a terminal countdown, then the option exists to make a second launch attempt as previously scheduled. If however the first launch attempt enters a terminal countdown, which results in a launch scrub, then it is likely that the next launch attempt(s) will need to be rescheduled.

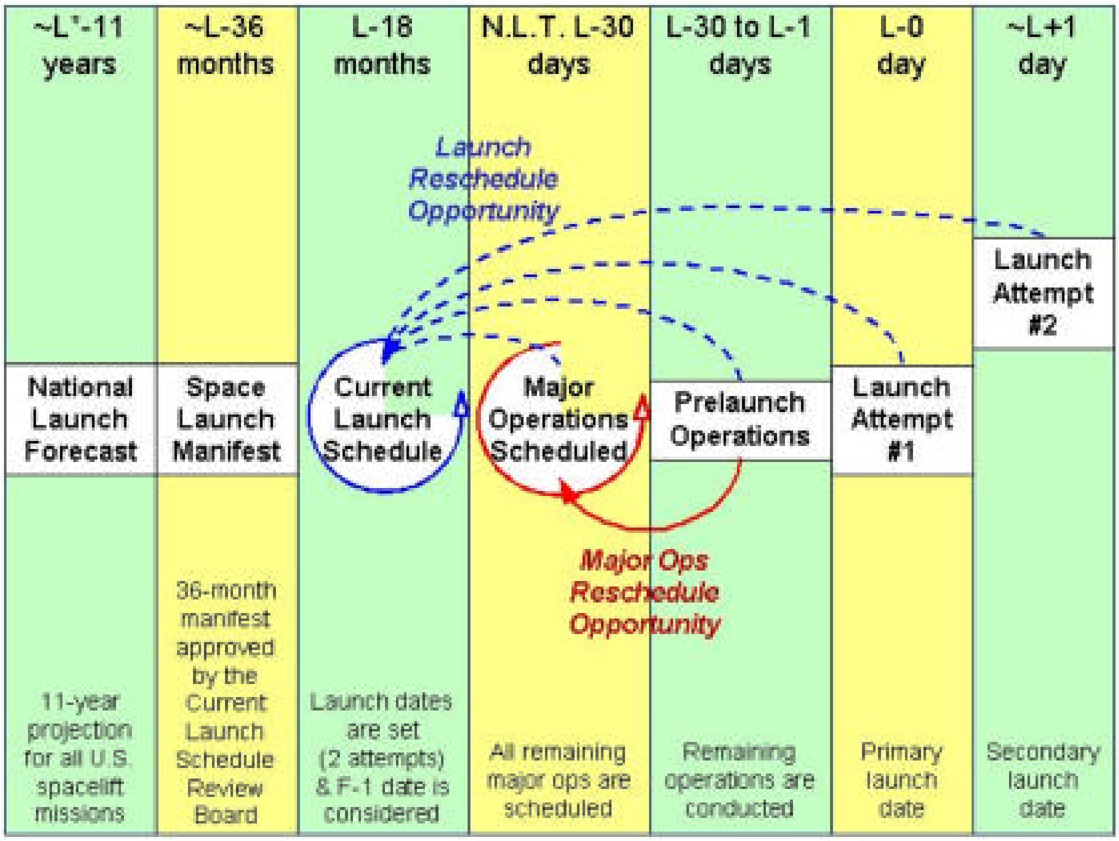

Figure 2.18: Launch Scheduling Timeline

2.8.1 Description of Primary Model Structure

This section of the system dynamics model covers the range scheduling process and involves a significant number of the variables within the model. For this reason the scheduling process is presented according to the following three subsections:

1. Consideration of a support request

2. Rescheduling of a support request

3. Allocation of range support

It is important to acknowledge that the approach chosen to model the scheduling of range support differs from the reality of the process as previously described. Rather than simulating the planning process, and the associated scheduling of activities years in advance of when they actually occur, the model was developed with the intent of accounting for the impact of such behavior while focusing on the actual operations and activities as they become necessary and are performed.

2.8.1.1 Consideration of a Support Request

Once a modeled launch program has reached the point in a launch flow when it is ready to conduct an operation with range support, it will submit a request for range support. Each request is comprised of two parts. One part states the duration of necessary range support while the other part classifies the operation as being either major or minor.

In response to every outstanding request for support, the model re-evaluates the request to determine if the required range support could be granted at the current time. The following filter-criteria are used by the model to determine whether a request should be considered, with the associated variable dependencies presented in Figure 2.19, Figure 2.20, and Figure 2.21:

- *'…{Today Restricted}'* -determines if a request should be considered based on whether today is restricted
- *'…{Single Major Support}'* -denotes whether there is any continuing major support activity, thereby precluding the consideration of any new request for major range support
- *'…{Maintenance Restriction}'* -determines if a request should be considered based on whether range maintenance is being performed, 1=Consider Request, 0=Do Not Consider Request
- *'…{Range Lockdown}'* -determines if a request should be considered based on range lockdown conditions
- *'…{Restricted Day Lookout}'* -determines if a request should be considered based on projecting whether or not the activity would carry-over into a restricted period of time
- *'…{Calendar Week Workload}'* -determines if a request should be considered based on range crew calendar week workload conditions
- *'…{Shift Workload}'* -determines if a request should be considered based on range crew work shift guidelines
- *'…{Continuous Days Workload}'* -determines if a request should be considered based on range crew continuous days workload conditions

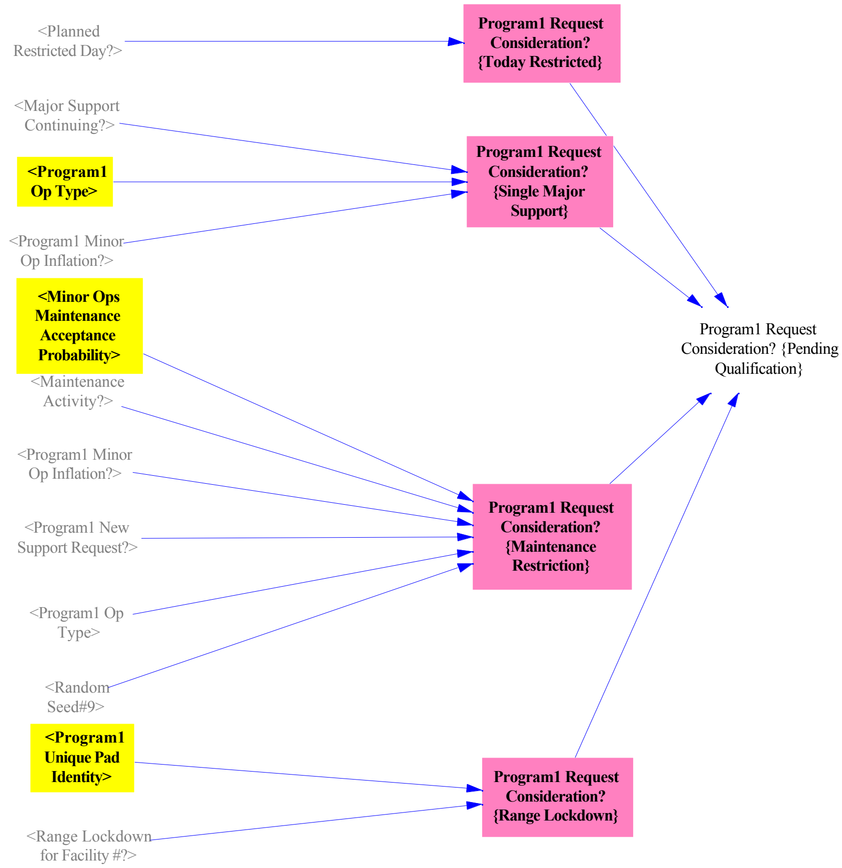

Figure 2.19: Scheduling (Model Structure 1- Request Consideration 1)

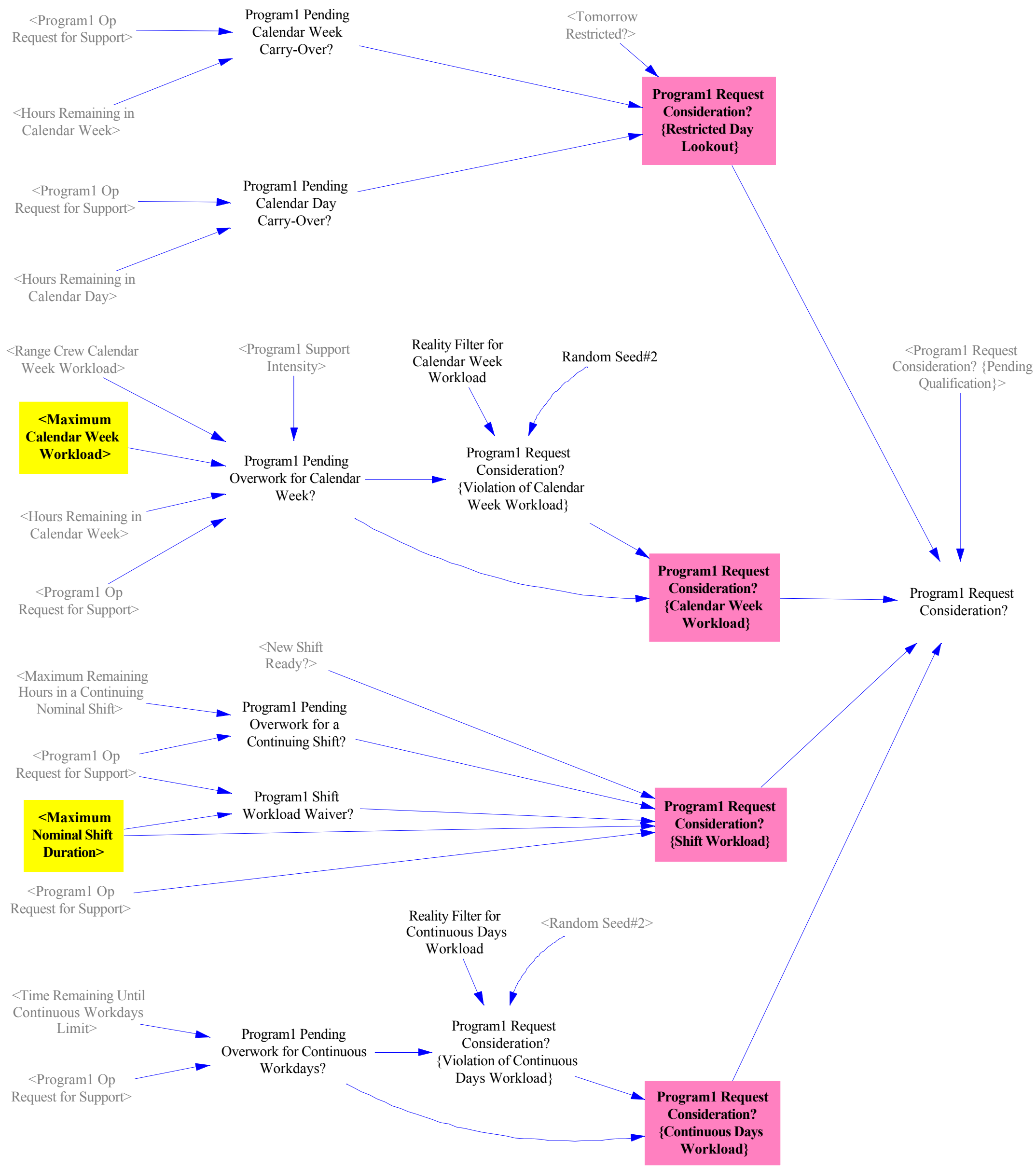

Figure 2.20: Scheduling (Model Structure 2- Request Consideration 2)

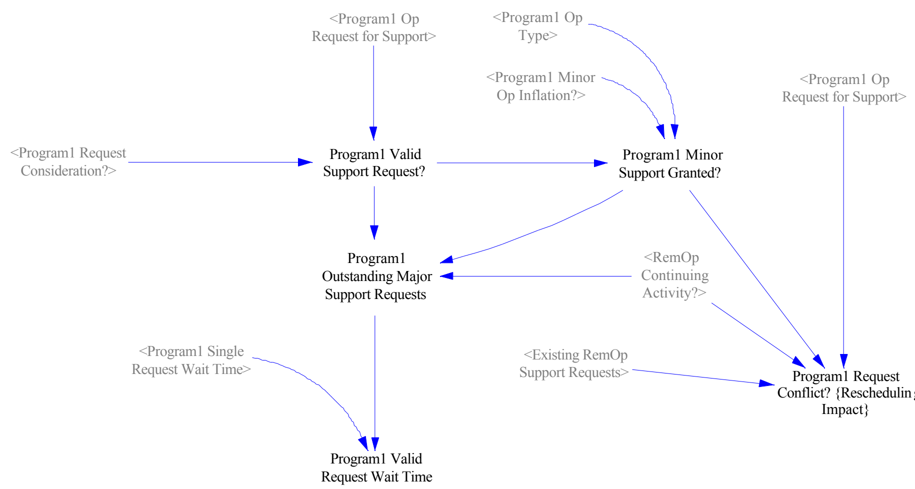

Figure 2.21: Scheduling (Model Structure 3- Request Consideration 3)

2.8.1.2 Rescheduling of a Support Request

For various reasons, range time previously scheduled in support of launch operations is rescheduled. This thesis does not investigate the underlying reasons of why this behavior exists, but rather acknowledges that it affects the availability of range support and attempts to form a quantitative framework to measure its impact.

Based on Eastern Range scheduling estimates, a variable called the *'Rescheduling Remnants Utilization Factor'* was created (USAF 1999). This variable represents a fraction defined as the aggregate duration of all scheduled range time ultimately used to support operations divided by the sum of the mutually exclusive utilized and unused (but previously scheduled) time. Obviously the inclusion of such a factor is completely exogenous and will subsequently have considerable impact on the output of this model section.

The approach employed by the model is to effectively create "wasted" range time at a rate influenced by the *'Rescheduling Remnants Utilization Factor'*. A similar technique was used to model the generation and consideration of actual requests for range support. Thus the structure of these subsections bear resemblance to analogous parts of the launch operations section (see thesis section 2.5.1) and the consideration of a support request section (see thesis section 2.8.1.1).

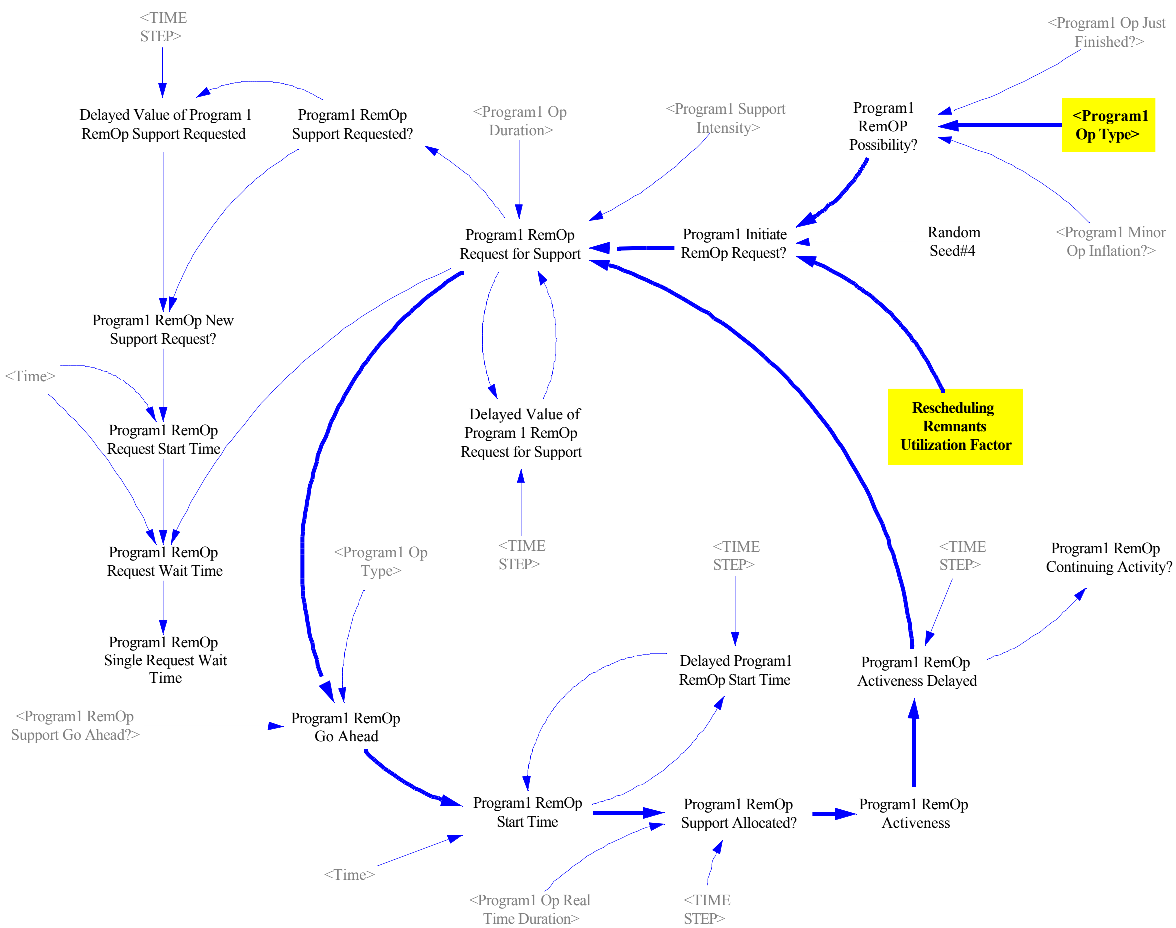

Figure 2.22: Scheduling (Model Structure 4- Rescheduling 1)

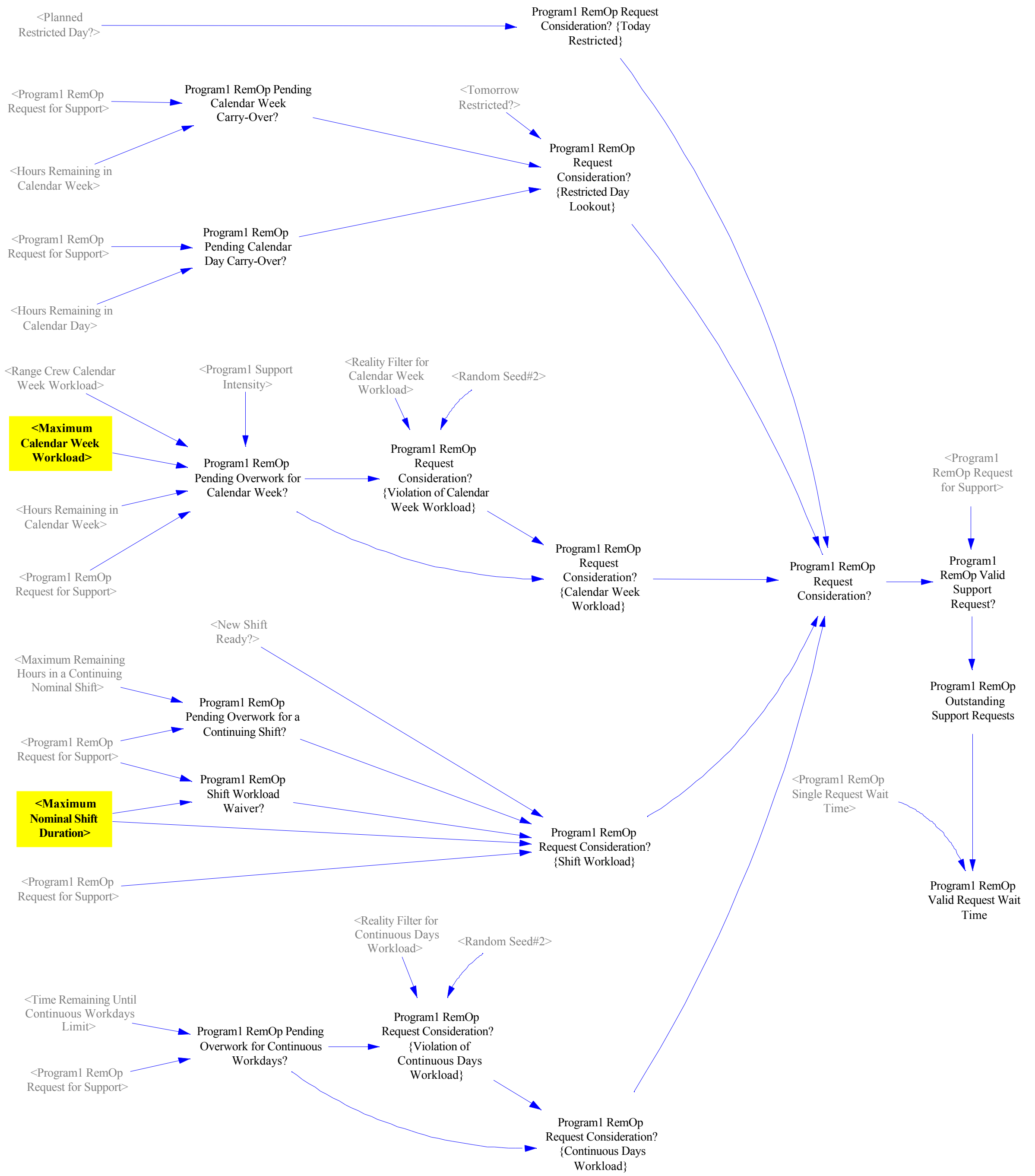

Figure 2.23: Scheduling (Model Structure 5- Rescheduling 2)

2.8.1.3 Allocation of Range Support

Qualified requests for range support, which have been filtered as "supportable", must subsequently be prioritized before any resources can be allocated. After the appropriate request(s) has been chosen, the model grants a "go ahead" to begin the operation. This function is achieved by implementing the following hierarchy when prioritizing requests:

1. **RemOps**- (labeled for "remnant operations") virtual operations that account for the impact of rescheduling and receive the highest priority

2. **Valid Request Wait Time**- secondary priority is awarded to the request(s) with the longest wait time

3. **Lottery**- if multiple requests exist with the highest combination of the first two criteria, then one of the requests is selected by a random lottery process

The following figures are presented in order to give the reader a sense of the primary dependence of variables involved with this model subsection and do not reflect the complete structure of the model subsection.

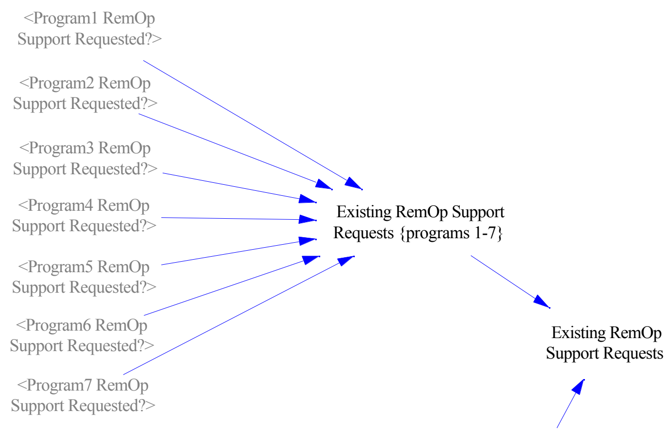

Figure 2.24: Scheduling (Model Structure 6- Support Allocation 1)

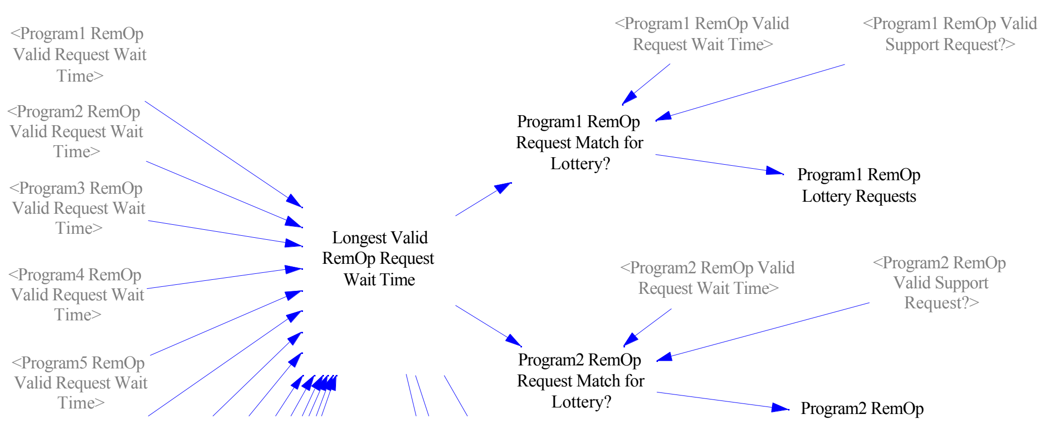

Figure 2.25: Scheduling (Model Structure 7- Support Allocation 2)

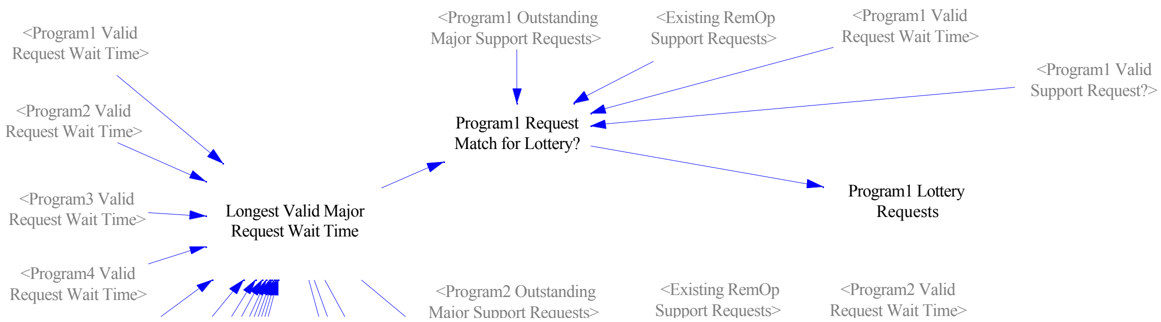

Figure 2.26: Scheduling (Model Structure 8- Support Allocation 3)

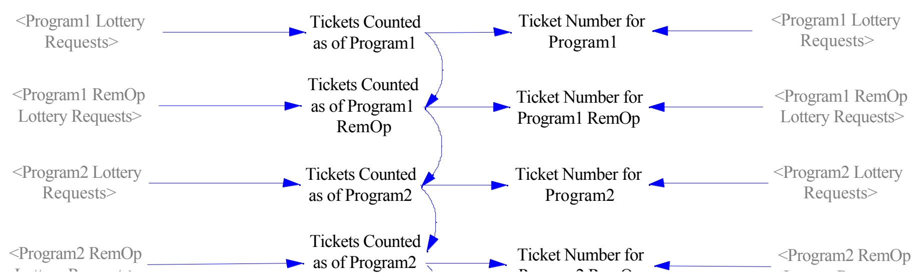

Figure 2.27: Scheduling (Model Structure 9- Support Allocation 4)

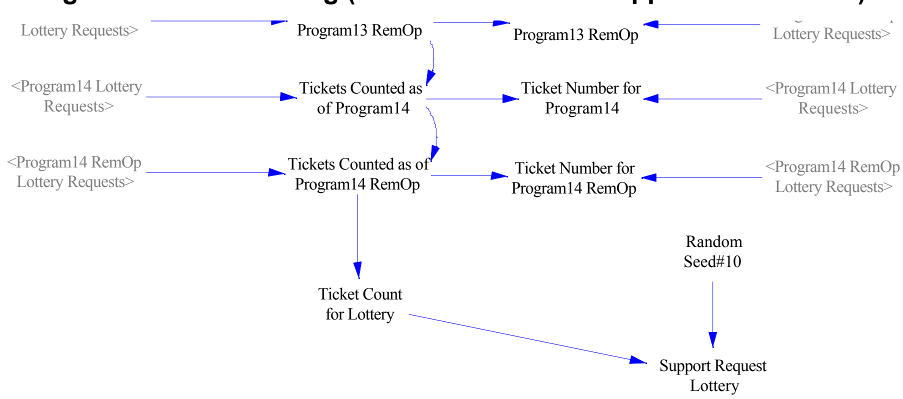

Figure 2.28: Scheduling (Model Structure 10- Support Allocation 5)

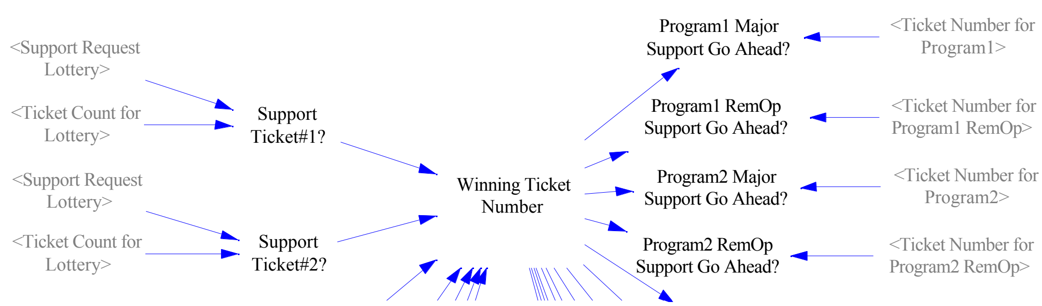

Figure 2.29: Scheduling (Model Structure 11- Support Allocation 6)

2.8.2 Model Inputs and Exogenous Variables

The principal inputs to this section include the following variables, which are directly dependent upon values supplied by a model user; thus their root causes are not explicitly addressed by existing model relationships:

'Program1 Op Type' -(Units: Dmnl)
Description: operation type defined as 1:major op, 2:minor op, 0:minimum interim

'Minor Ops Maintenance Acceptance Probability' -(Units: Dmnl)
Description: probability that a standard minor operation (Non-inflated) can be supported during an arbitrary maintenance period

'Program1 Unique Pad Identity' -(Units: Dmnl)
Description: denotes a unique number used to identify this launch facility for internal modeling purposes

'Maximum Calendar Week Workload' -(Units: RangeHours)
Description: maximum number of hours the crew is allowed to work within a single calendar week

'Maximum Nominal Shift Duration' -(Units: Hours)
Description: maximum allowed duration for a range crew shift of work under nominal circumstances

'Rescheduling Remnants Utilization Factor' -(Units: Dmnl)
Description: a ratio representing the aggregate duration of all scheduled range time ultimately used to support operations divided by the sum of the mutually exclusive utilized and unused but previously scheduled time {value must be within the range of 0 to 1}

2.9 Range Statistics

The primary function of the range statistics section of the model is to compile values that may be of particular interest to a model user. It should be noted that this section does not contain any model inputs or exogenous variables. The section can be thought of as an output module; as such it does not actually contain any crucial variable relationships that feedback into other sections of the model.

2.9.1 Description of Primary Model Structure

Many of these variables are configured to provide a convenient measure of system performance. The variables contained in this section were created to aid a model user in the analysis of launch operations at the Eastern Range. The following figures provide the reader with partial views of the model structure for this section. The intention was to present enough information so that a basic level of comprehension of variable relationships can be attained without including an exhaustive presentation of non-crucial variables.

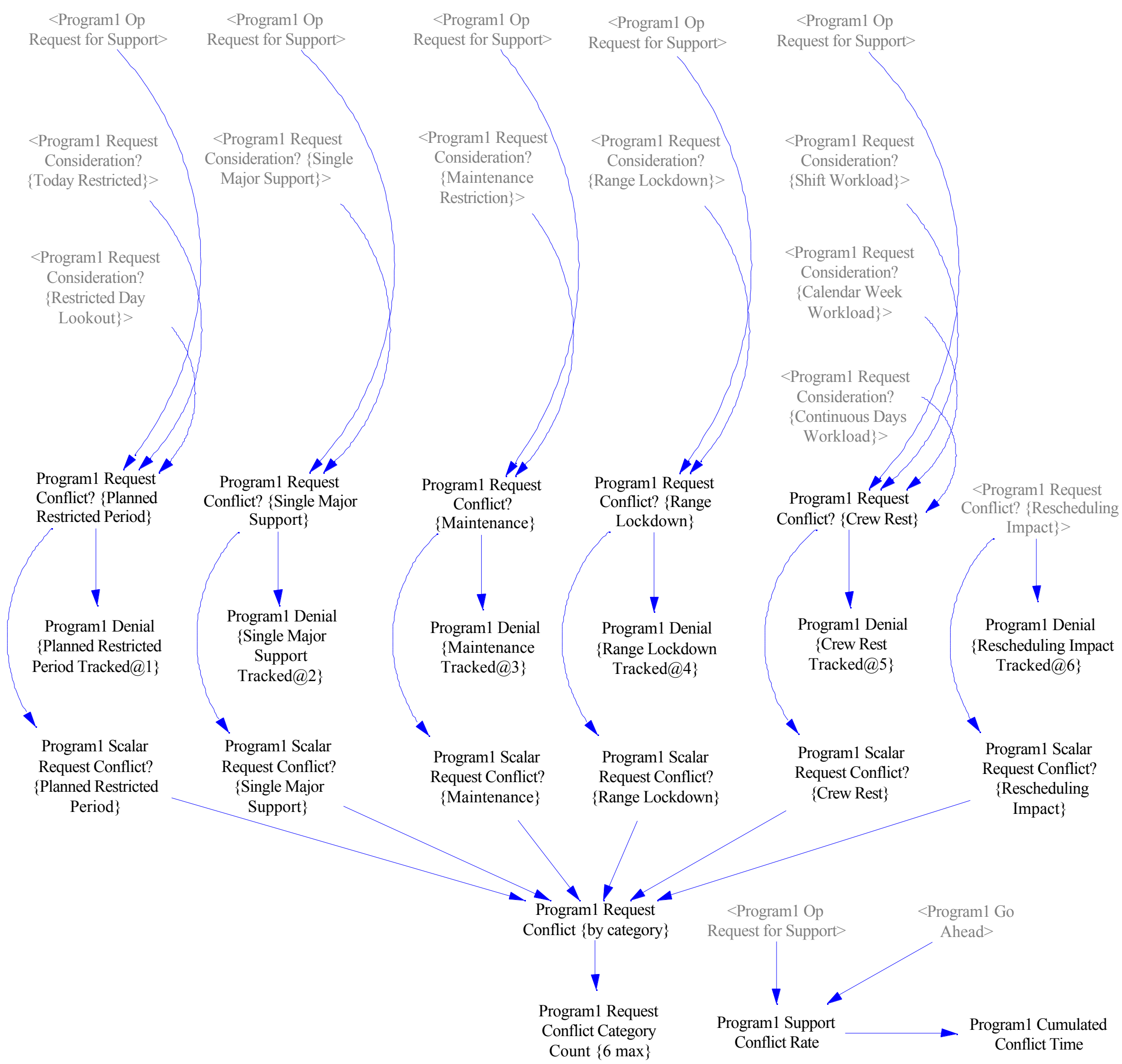

Figure 2.30: Range Statistics (Model Structure 1)

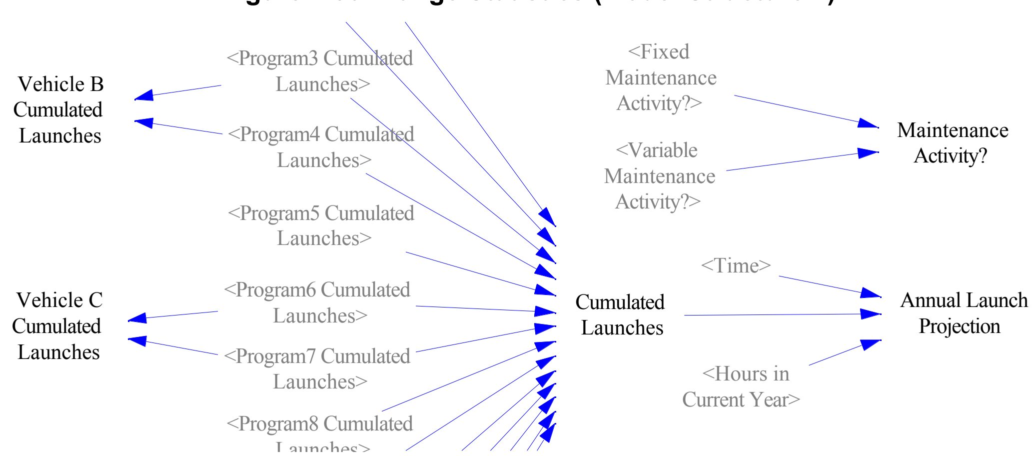

Figure 2.31: Range Statistics (Model Structure 2)

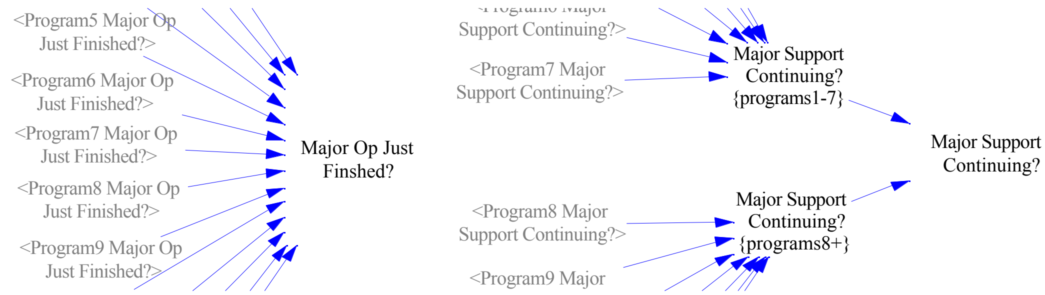

Figure 2.32: Range Statistics (Model Structure 3)

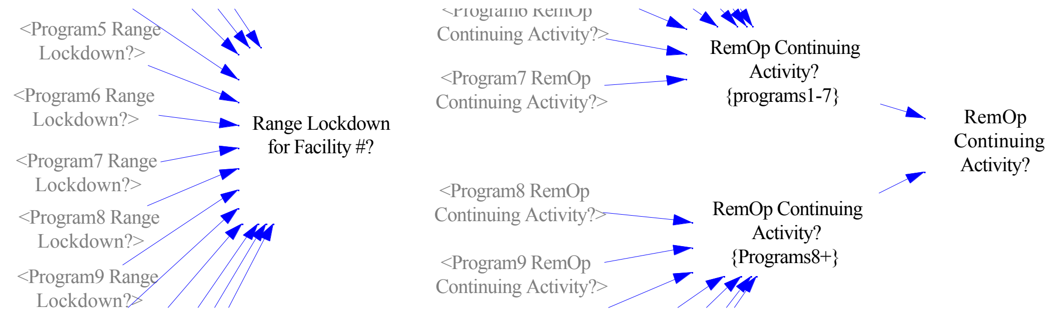

Figure 2.33: Range Statistics (Model Structure 4)

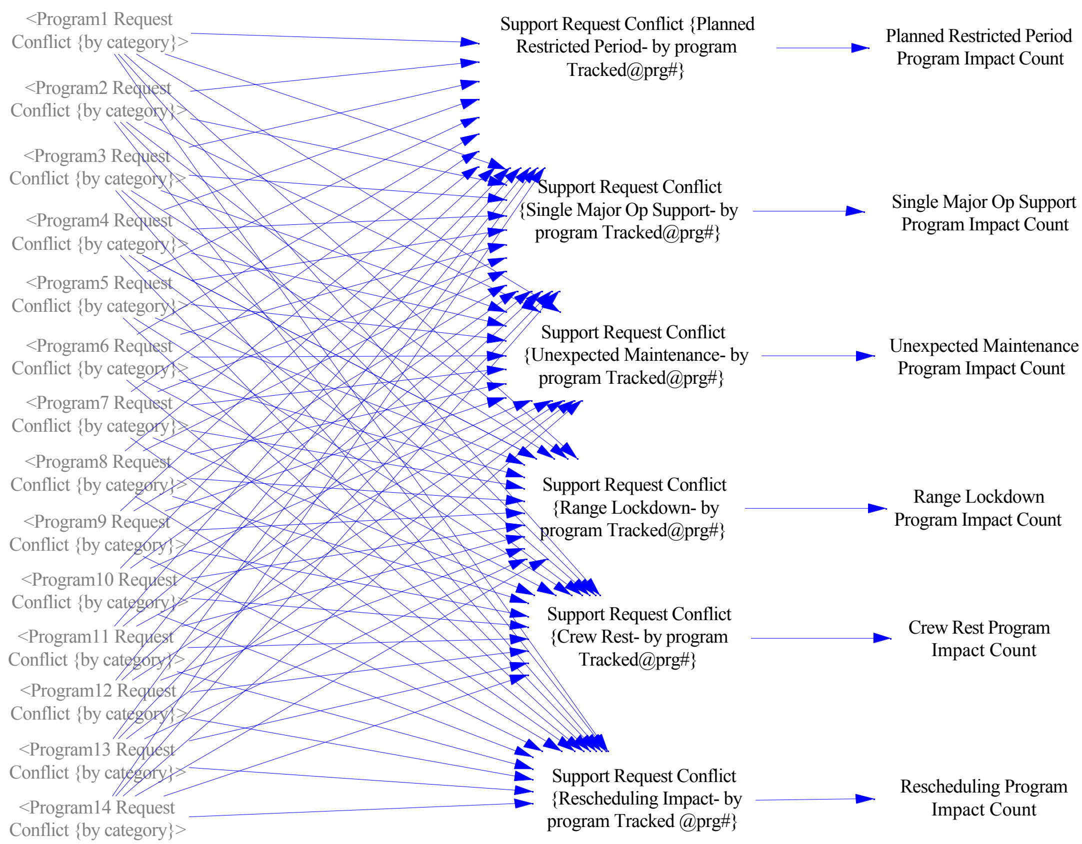

Figure 2.34: Range Statistics (Model Structure 5)

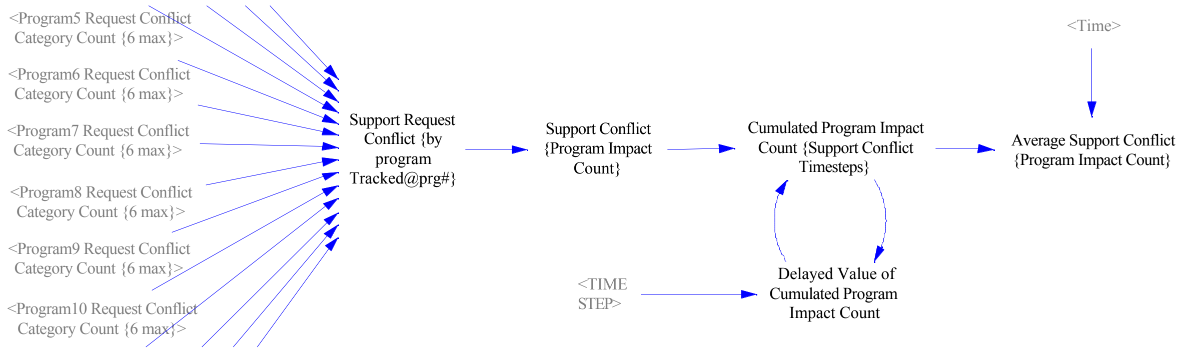

Figure 2.35: Range Statistics (Model Structure 6)

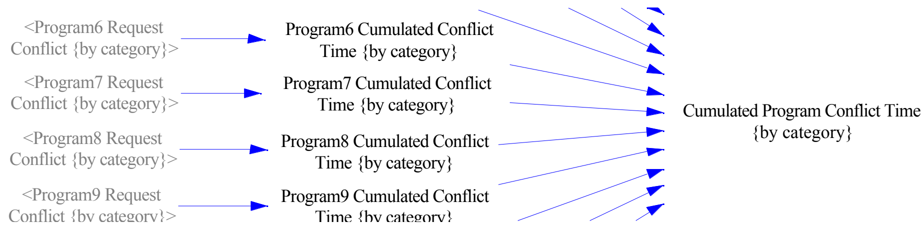

Figure 2.36: Range Statistics (Model Structure 7)

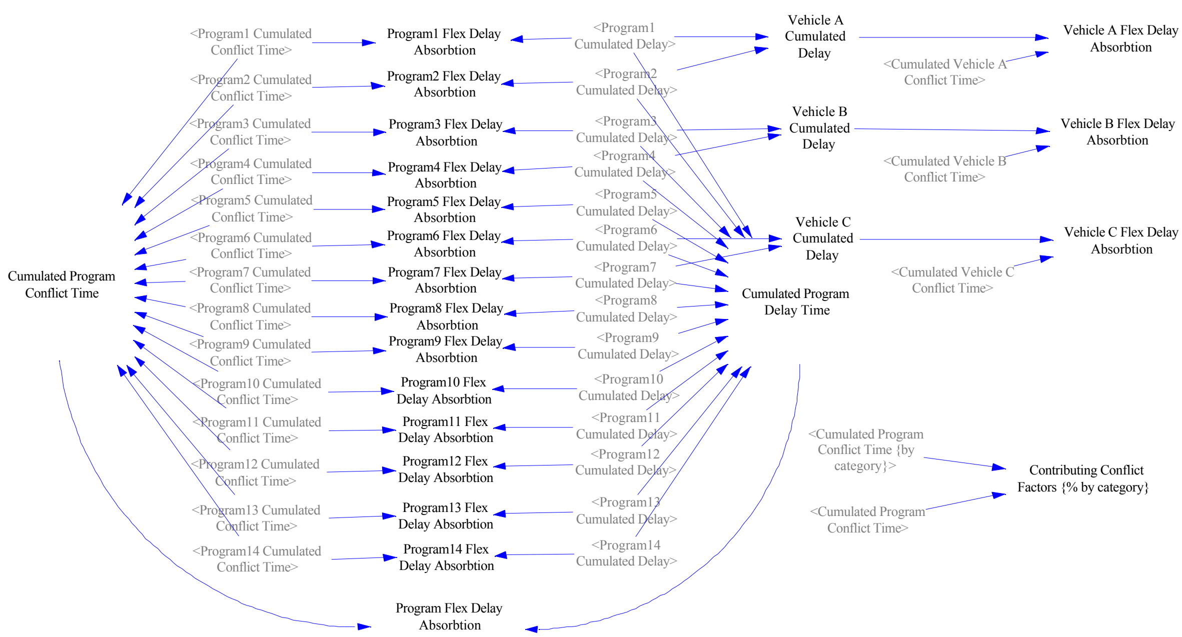

Figure 2.37: Range Statistics (Model Structure 8)

CHAPTER 3: LAUNCH OPERATIONS ANALYSIS

The focus of this chapter is to demonstrate the capability of the system dynamics model while providing further validation of its structure. The initial section explains how random variables have been incorporated into the design of the model, so as to reflect the uncertainty of specific values in the real world. The next few sections present various samples of model output that were produced from running a single simulation of the model, based on expected Eastern Range conditions for fiscal year 2001. The final section of this chapter provides the results of two detailed sensitivity analyses. The first analysis corresponds to analyzing the constraints of launch operations for the expected Eastern Range operating conditions during fiscal year 2001. The second sensitivity analysis was performed using a range capacity scenario for the same time period. The chapter concludes with a comparison between the expected and the range capacity conditions for FY01.

3.1 Random Values

Randomness is a characteristic of many systems. Variability between different simulations of the model arises from a collection of deliberate random variables. These variables account for the system uncertainty associated with the real world. This uncertainty exists, even when system behavior on a macroscopic level may be understood.

Such uncertainty, which drives the variability of model results, is termed *primary uncertainty*. Primary uncertainty is simply an accepted probability of occurrence. Launch scenarios using varying or probabilistic manifests or other parameters not specifically identified in the following list have yet to be analyzed. It is expected that by varying these other parameters (secondary uncertainty) simulation results may differ significantly; however, the concentration of the modeling effort thus far has been to identify the variability associated with primary uncertainty.

The only model input variables that were not held constant across the initial conditions of sensitivity testing were eleven types of *random variables*. These random variables served the following purposes:

1. *Assignment of Planned Restricted Days* based on a user input number of annual planned restricted days

2. *Allowance of Waivers to Range Crew Workload Guidelines* based on a user input probability (Note: this variable is not currently influential)

3. *Onset of Minor Operation Inflation* based on a user input probability of having an operation identified as a minor operation, but in reality requiring significant range resources on a level comparable to a major operation

4. *Onset of Schedule Change Impact* based on a user input probability of impact due to rescheduling of operations

5. *Onset of Fixed Maintenance* based on a user input rate of maintenance hours

6. *Duration of Fixed Maintenance* based on a series of user-defined possible maintenance durations

7. *Onset of Variable Maintenance* based on a user input rate of maintenance hours

8. *Duration of Variable Maintenance* based on a series of user-defined possible maintenance durations

9. *Onset of a Minor Operation During a Maintenance Period* based on a user-defined probability of a minor operation having the ability to be performed simultaneously with ongoing range maintenance activity

10. *Support Allocation Lottery* designates a single operation from a list of mutually exclusive operations

11. *Launch Program Campaign Spacer* based on a user input launch manifest and the remaining amount of time in the simulation

3.2 Restricted Periods

Recall from thesis section 2.4 that the model is configured to randomly assign restricted range dates based on an annual number of days specified by a user. Figure 3.1 shows an example of how the model determined which days were restricted during the course of a single simulation of FY01. For this simulation a value of 40 restricted days was initially entered into the model. The graph depicts the count of restricted days as the simulation progresses through all twelve simulated months. If the model had been configured to run a second simulation of this same scenario, a similar plot to that shown in Figure 3.1 would have taken a different route to eventually reach a total of 40 restricted days.

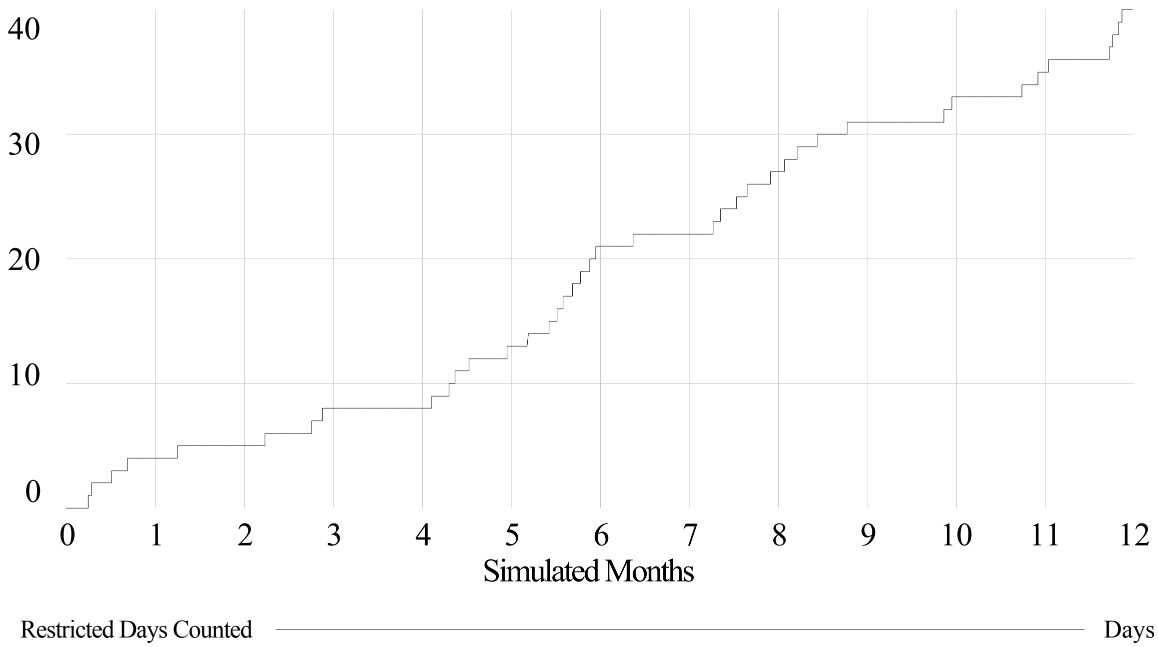

Figure 3.1: Restricted Days Counted (Plot)

3.3 Launch Vehicle Operations

As described in thesis section 2.5, a launch program requires range support at specific points or during certain periods of time throughout a launch flow in order to conduct some operations. Figure 3.2 shows when Launch Program ‘X’ required range support during a single simulation of the model for FY01 launch manifest conditions.

In this chart there are a series of 4 clusters of “spikes” where each cluster contains the same sequence of 5 vertical bars. Every cluster of “spikes” corresponds to a separate launch campaign conducted by Launch Program ‘X’. From this explanation one can determine that Launch Program ‘X’ conducted a series of 4 launches during the simulated year.

Each of the vertical bars corresponds to a specific request for range support from Launch Program ‘X’ to conduct an operation using range resources. Since there are 5 vertical bars within each launch campaign, one can infer that there are 5 operations modeled for the launch flow of Launch Program ‘X’. The last two operations are specifically labeled as the ‘F-1’ range reconfiguration event and the actual ‘launch’ event, whereas the first three operations are not identified by an actual name.

The height of each bar denotes the duration of range support necessary to conduct the associated operation. The duration of each operation remains the same each time it is performed. For example, the first operation (Op 1) is conducted four times throughout the course of the year and always required 2 hours of range support.

As soon as the launch program was ready to conduct an operation, the model plots a vertical bar. Once range support is granted and the operation begins, the vertical bar returns to the horizontal axis. Therefore the width of each vertical bar represents the amount of time the launch program remained ready to conduct an operation, but support was not immediately available.

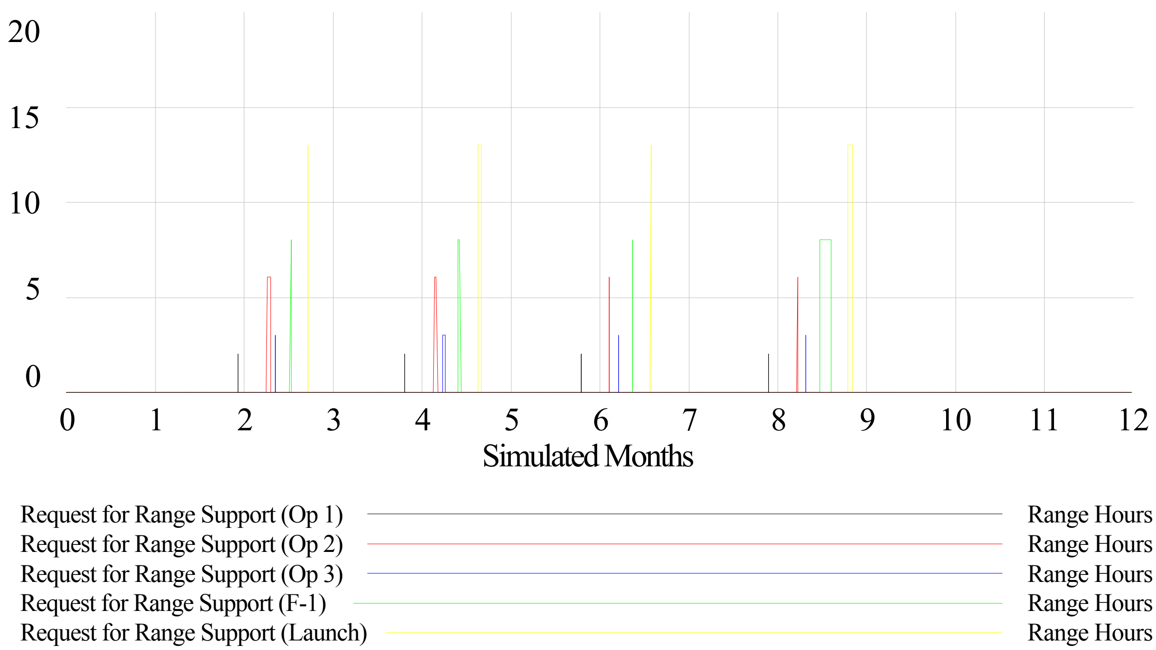

Figure 3.2: Pad 'X' Requests for Range Support (plot)

The wait times that Launch Program ‘X’ experienced before range support became available are specifically plotted in Figure 3.3. In this chart the launch program wait times are measured in calendar hours and occur at the peak of each plot.

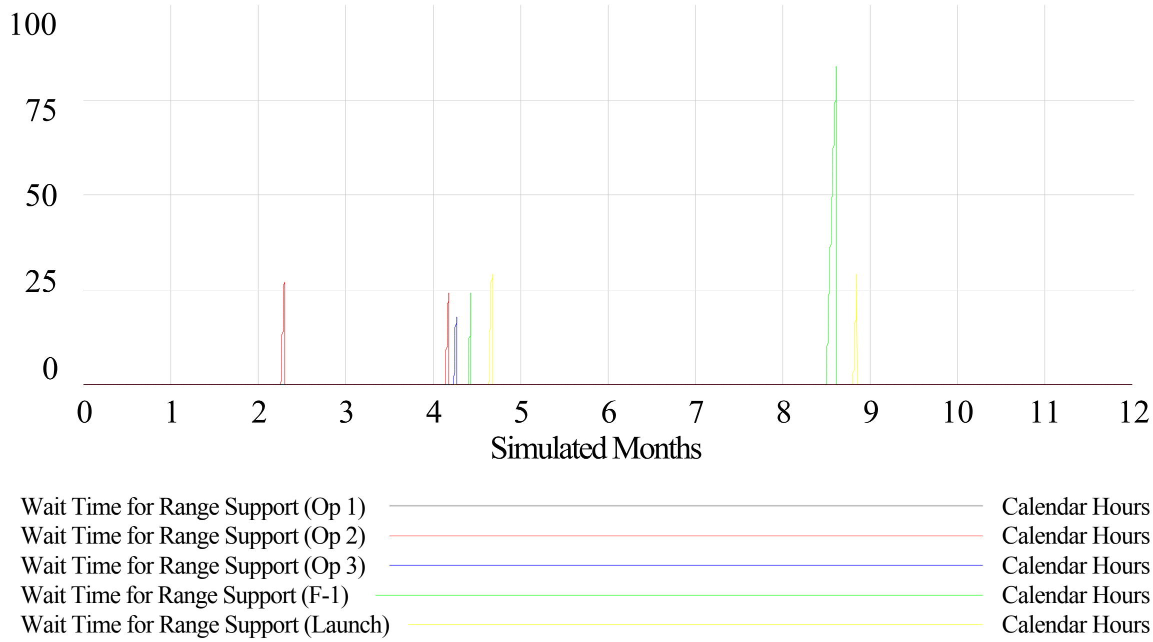

Figure 3.3: Pad 'X' Wait Times for Range Support (plot)

Various factors may contribute to the unavailability of range support. Each of these factors has been classified into one of the following six categories:

1. **Planned Restricted Period**
2. **Single Major Operation Support**
3. **Unexpected Maintenance**
4. **Range Lockdown**
5. **Range Crew Rest**
6. **Rescheduling Impact**

Planned Restricted Period- this is a preplanned event that renders range resources unavailable to support launch-related operations. Examples include holidays, time for training exercises, and range upgrade activities.

Single Major Operation Support- by definition, a major operation requires such an extensive amount of range resources that only one major operation may be supported at any given moment.

Unexpected Maintenance- this is unplanned maintenance, which is undertaken in response to an event and must be performed within the immediate timeframe in order to restore the range to a nominal working status.

Range Lockdown- the period of time between the completion of an F-1 range reconfiguration operation and a launch, during which time the only program that may receive range support for a major operation is the program for which the range has been reconfigured for launch.

Range Crew Rest- reserved periods of time between shifts, which serve to keep workload levels of the range crew within safety guidelines.

Rescheduling Impact- amount of time previously allocated to support range operations, which is ultimately not utilized by any launch program.

Figure 3.4 is used as an example to describe how the model keeps track of which categories prevent a request for range support from being fulfilled immediately. The chart depicts one episode from a single run of the model when range support was unavailable and a launch program had to wait before it could conduct an unspecified operation. In this view the horizontal axis shows the time during the year when the situation has occurred. In this example, the launch program requested range support shortly before day number 332. The vertical axis is used to track which of the six categories of possible support conflict contribute to the unavailability of range support. At the onset of the request for support, both categories 3 (*Unexpected Maintenance*) and 5 (*Range Crew Rest*) prevent the operation from beginning. A few hours later, only category 3 (*Unexpected Maintenance*) prevents the operation from being conducted. Around the middle of day 332 category 1 (*Planned Restricted Period*) becomes an additional factor to holding back the operation. Late during day number 333 the restriction due to category 3 (*Unexpected Maintenance*) is lifted, but category 1 (*Planned Restricted Period*) continues to prevent the operation from starting. Finally, just as day 334 begins, no restrictions remain and the operation is allowed to begin.

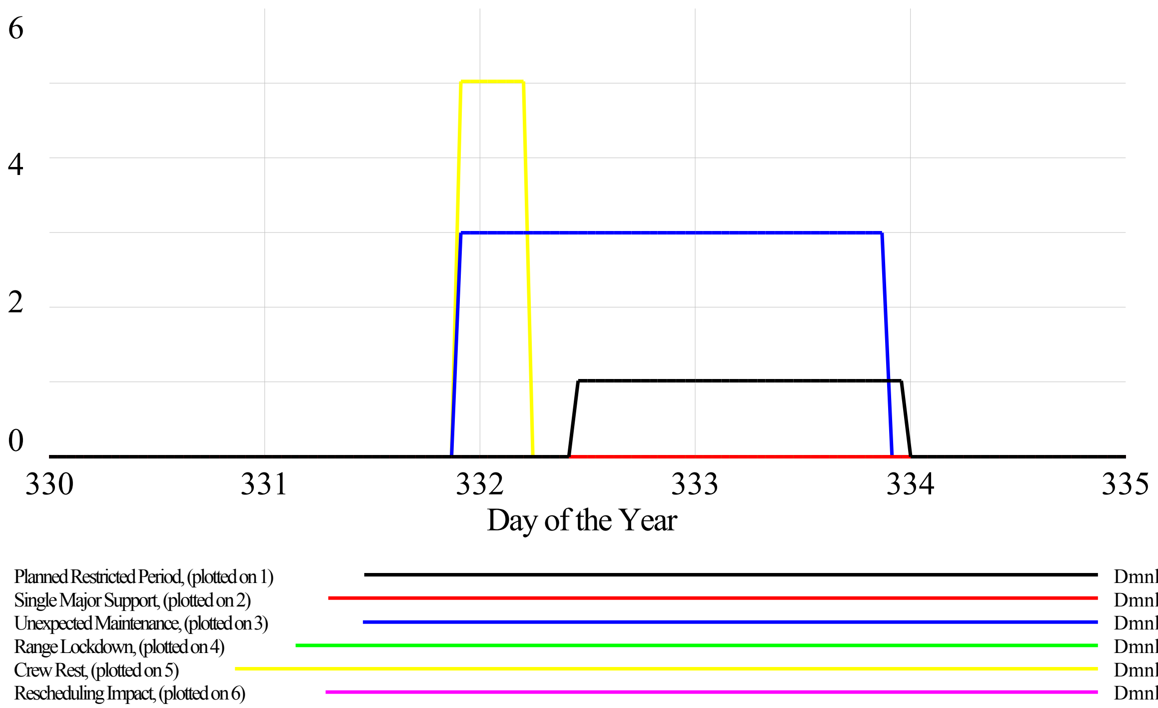

Figure 3.4: Unavailability of Range Support (plot)

3.4 Range Crew

Figure 3.5 shows a graph of the cumulated range crew workload on a weekly basis for a single simulation of an FY01 scenario. Considering there are approximately 52 weeks in a single year, the graph includes roughly 52 "columns". The peak of each "column" represents the cumulated hours of launch-related work for the corresponding week.

Recall from thesis section 2.6 that one of the range crew workload guidelines is no more than 60 hours per workweek. Figure 3.5 suggests that this guideline is not a limiting factor for FY01 because the plot rarely approaches this weekly threshold. Another observation from the graph is that potentially demand for range support may fluctuate significantly from week to week.

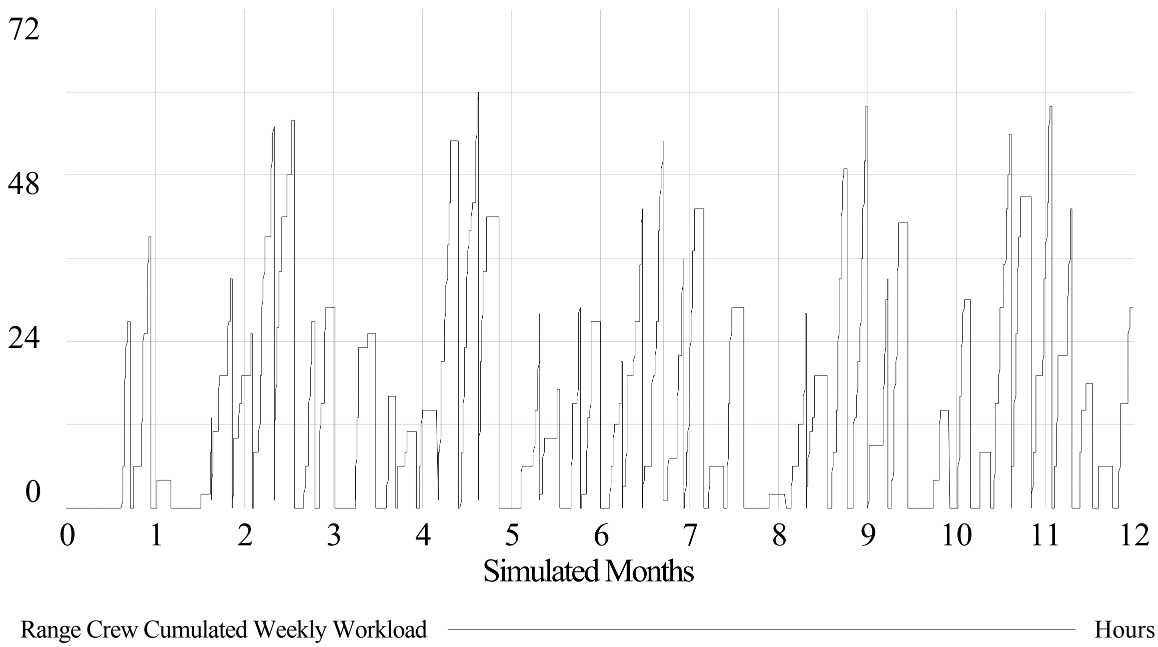

Figure 3.5: Range Crew Weekly Workload (plot)

Figure 3.6 shows the number of continuous days worked by the range crew during a single run of the model. Keeping in mind that the workload guideline was to not have the crew work in excess of 14 consecutive days, during this simulation of the model there was no apparent instance when the crew worked beyond 10 consecutive days. This graph suggests that the consecutive day guideline is not a major constraint.

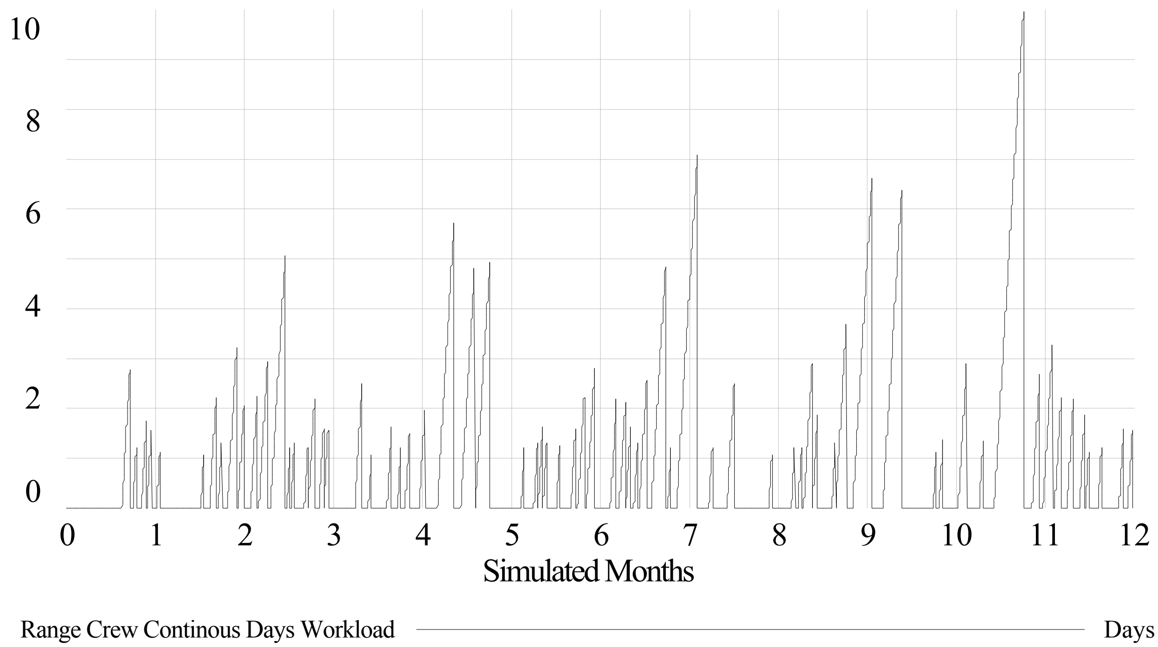

Figure 3.6: Range Crew Continuous Days Workload (plot)

3.5 Range Systems Maintenance

Sensitivity analyses were performed on both fixed and variable maintenance activities. Each analysis included running the model one hundred times based on the same initial conditions. In the following case the model input values included the FY01 Eastern Range launch manifest.

The cumulated fixed maintenance hours for each of the one hundred simulations of FY01 are depicted in Figure 3.7. This chart shows the data from all one hundred simulations as a series of colored confidence bounds. The central light-colored region of the plot represents the middle 50% of all of the simulations. The mean value of all the simulations is plotted as a single dark line through the center of this region. Similarly, darker and darker bands of color surround the central light band and represent regions through which individual simulations plotted values, but at farther levels away from the average value.

Figure 3.7 aids in validating the model. For each of the simulations performed during the sensitivity test, the model input value for the variable *'Annual Fixed Maintenance Time'* was set at 240 hours. For each of the simulations the model successfully demonstrated an end of year value totaling 240 hours of fixed maintenance. The mean plot was nearly linear, which was also expected. An additional validation is that the model equally distributed both high and low concentration periods of fixed maintenance activity at different points throughout the simulated year.

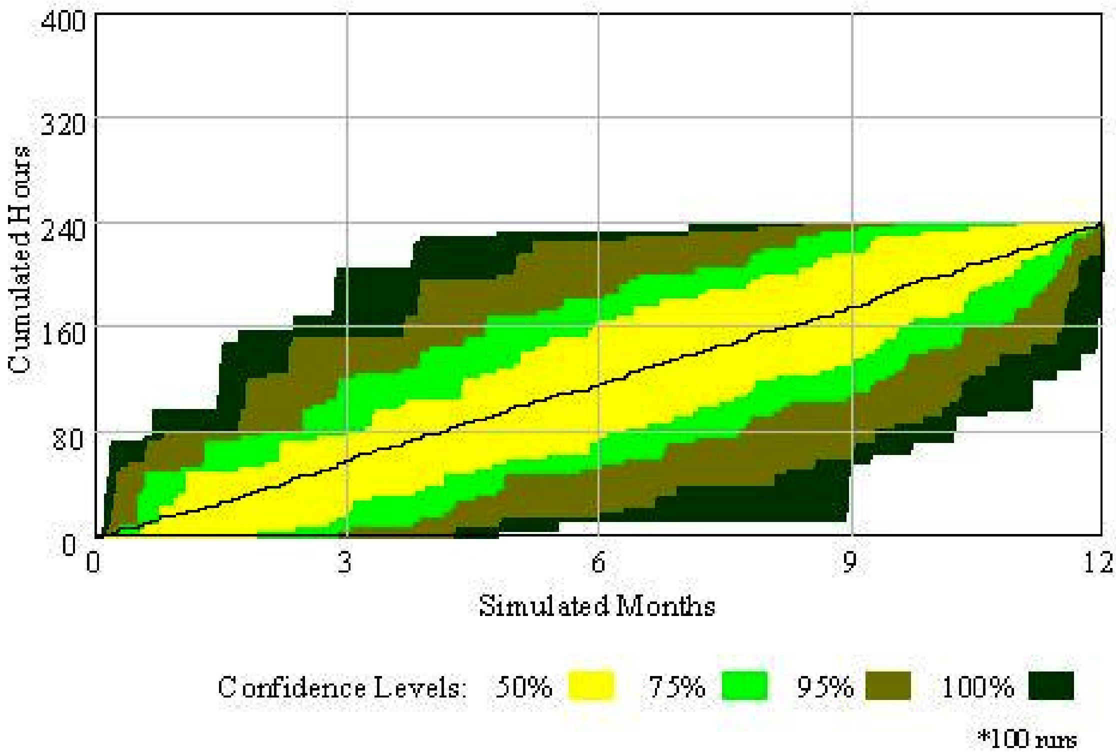

Figure 3.7: Range Systems Fixed Maintenance (plot)

The cumulated variable maintenance hours from the same series of sensitivity simulations is shown in Figure 3.8. This graph bears some resemblance to the previous one with a couple subtle differences. One observation is that the end of year values, for the amount of cumulated variable maintenance time, become a distribution of values rather than converge at a single point. This result is due to the probabilistic methodology of modeling this type of maintenance as described in thesis section 2.7.1.2. The model predicts an average value of roughly 320 hours of variable maintenance can be expected during FY01 with limits as high as around 420 hours and as low as 160 hours observed.

An additional observation of Figure 3.8 is that the plot appears to suggest a slight nonlinear quality for variable maintenance activity. This effect is simply due to a simplification residing in the model. In actuality there is no apparent reason why variable maintenance should not occur with as much linearity as fixed maintenance. The nonlinear effect is small enough so that the model currently predicts values within an acceptable level of accuracy for this thesis. This acknowledged error is most likely caused by the way in which launch campaigns are spaced out from each other, which results in a slightly increasing rate of operations and therefore a slightly increasing rate of variable maintenance.

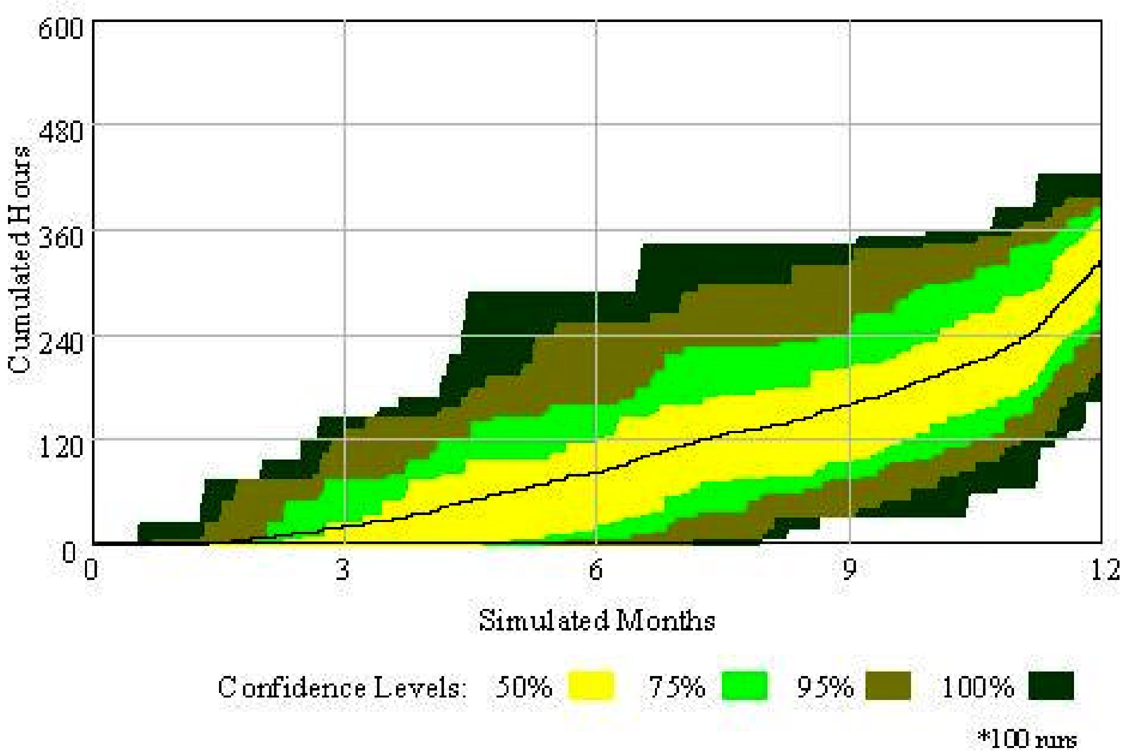

Figure 3.8: Range Systems Variable Maintenance (plot)

3.6 Range Statistics

The analysis information presented thus far has been focused on showing the utility of the model. All of the corresponding data plots were selected to simply convey examples of some of the types of output the model is capable of producing. The following sections of analysis are included for two reasons. As before, these analyses continue to introduce the reader with additional functionality of the model. In addition, particular values are presented based on their relevance to understanding range launch operations and the importance they play in the strategic planning of future space launch operations.

Fiscal year 2001, (October 1, 2000 through September 30, 2001) was selected as the case example year for the numerical values presented in this thesis. This timeframe was chosen due to the high level of confidence associated with certain model input variables, such as the annual launch manifest, and also because of a desire to use the model for predicting future values.

Two primary operating scenarios were analyzed and are discussed in this section. The first scenario corresponds to the actual launch operations expected to occur in FY01. This analysis is included to give the reader a sense of what to expect in the next year and to benchmark a realistic scenario of operations, which can be compared to the current level of understanding and known behavior of modeled variables.

The second scenario corresponds to the Eastern Range operating at launch capacity conditions for FY01. This analysis is presented to be used as a comparison to the expected FY01 scenario and to provide a sense of launch operations constraints during this timeframe.

3.6.1 Expected Operating Conditions for FY01

The following analysis was performed using the Eastern Range 2001 fiscal year launch manifest and serves as an example of model functionality (USAF 2000). The system dynamics model was configured to run a series of one hundred simulations of this case year. The uncertainty of specific output variables was subsequently determined by comparing the results of these different model simulations.

Figure 3.9 is a step plot showing the expected number of cumulated launches throughout the course of FY01. This figure depicts the traces of all one hundred runs of the sensitivity analysis. The mean value of these simulations is fairly linear and is represented as the central light-colored line.

It becomes apparent by this graph that, for any specific time during the year, the number of expected cumulated launches is uncertain. For example, at six months into the year the number of cumulated launches has been found to vary from 12 to 19, as can be seen in Figure 3.9. This trait of the model is most realistic for years further into the future and becomes less accurate for the immediate launch manifest, which includes scheduled launch dates and a higher degree of manifest stability.

Another observation of Figure 3.9 is the apparent lag time or transient period before a "stabilized" launch rate is established. This effect is the result of a simplification used to model the launch vehicle operations in the current version of the model. At present, the model is configured to credit a launch only after all the associated prelaunch operations have been simulated. Due to this limitation, a launch will not be credited until an entire launch campaign has elapsed.

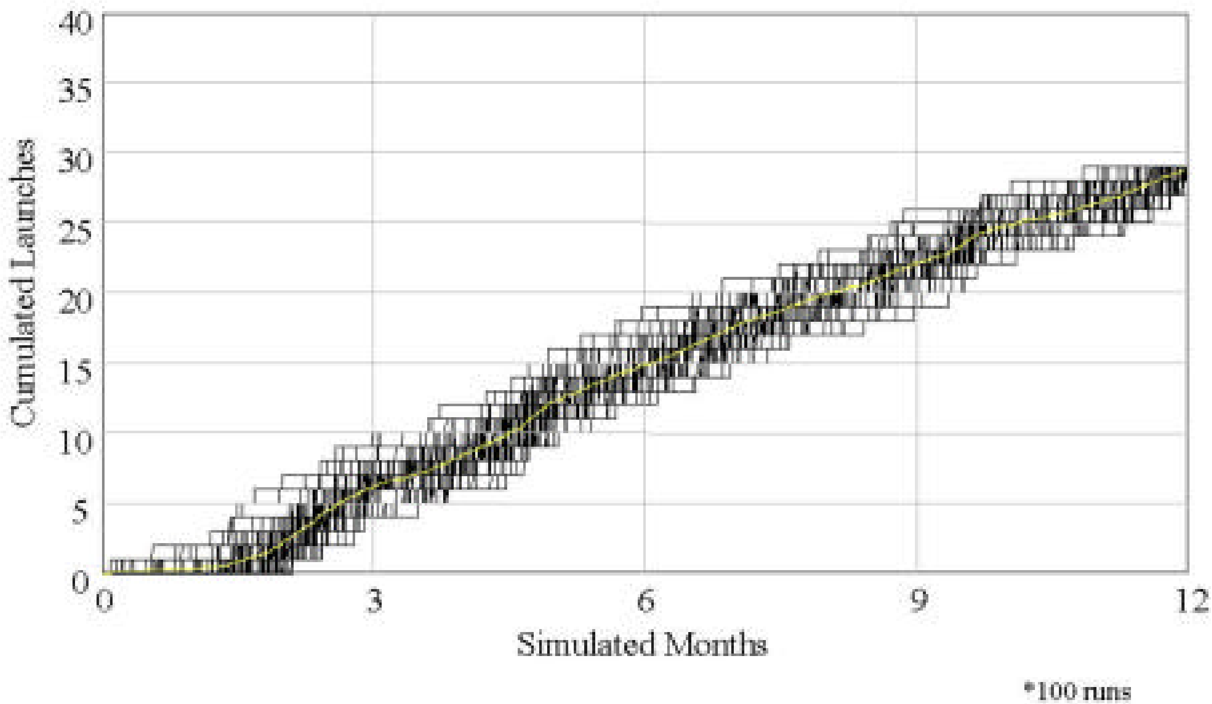

Figure 3.9: Cumulated Launches for FY01 (plot)

3.6.1.1 Range Support Conflicts for FY01

A measure of the congestion level to be expected on the range for FY01 is provided in Figure 3.10. This sensitivity plot portrays the average number of launch programs expected to be in need of range support, without having been granted range support, at any given moment during the year. The mean value was calculated to be slightly less than 0.3 launch programs. The inverse interpretation of this result is to expect that roughly 1 hour out of any 3.5 hours during the year will be a period of time when a launch program is denied range support[4].

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[4] The Eastern Range FY01 launch manifest used in this analysis included various degrees of activity from a total of 9 launch programs.

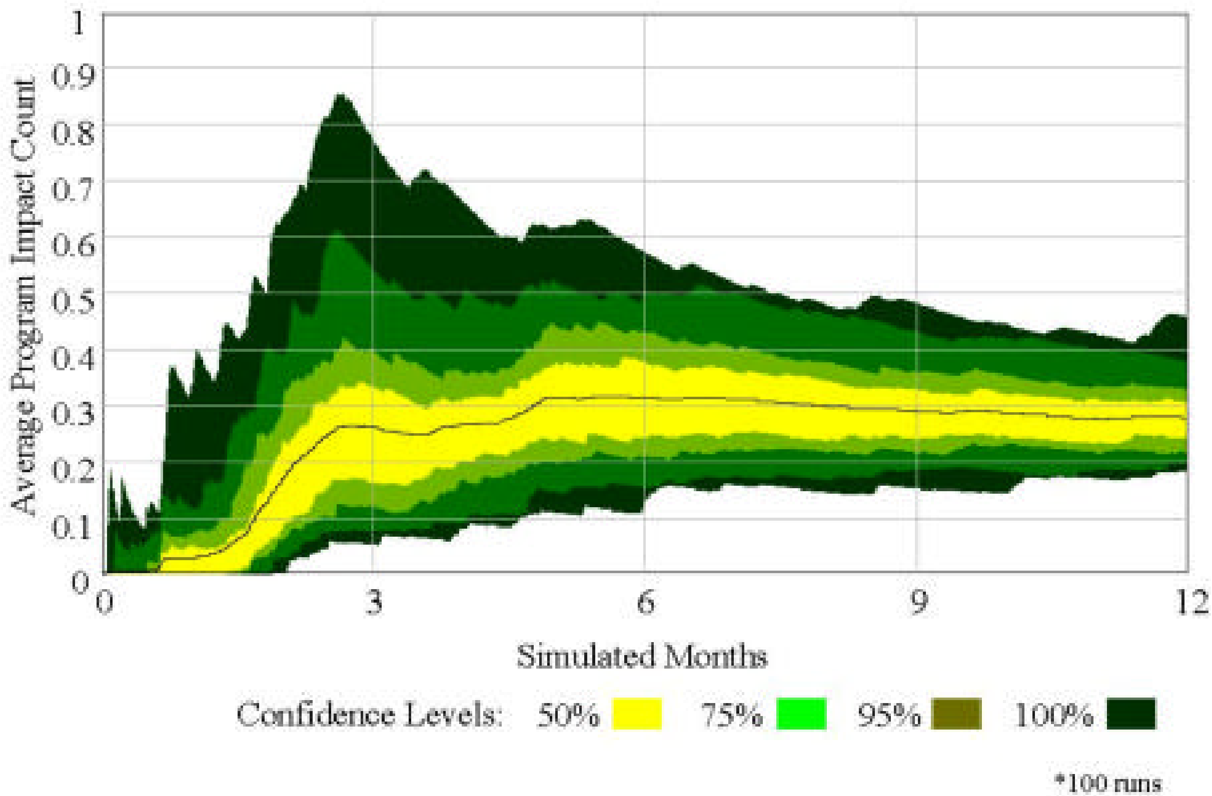

Figure 3.10: Expected Number of Programs with a Support Conflict at a Random Moment (plot)

The expected number of launch program calendar hours for which programs required, but did not receive, range support are depicted in Figure 3.11. This cumulated value of time is aggregated across all active launch programs. Therefore if two launch programs are both denied range support during the same hour of the year, the model will account for 2 program hours.

The mean value for the expected amount of launch program conflict time during FY01 is projected to be approximately 2,500 hours. The range of values produced through 100 simulations of the model varied from approximately 1,700 hours to just over 4,000 hours with varying degrees of associated probability. The corresponding confidence bounds are displayed in Figure 3.11.

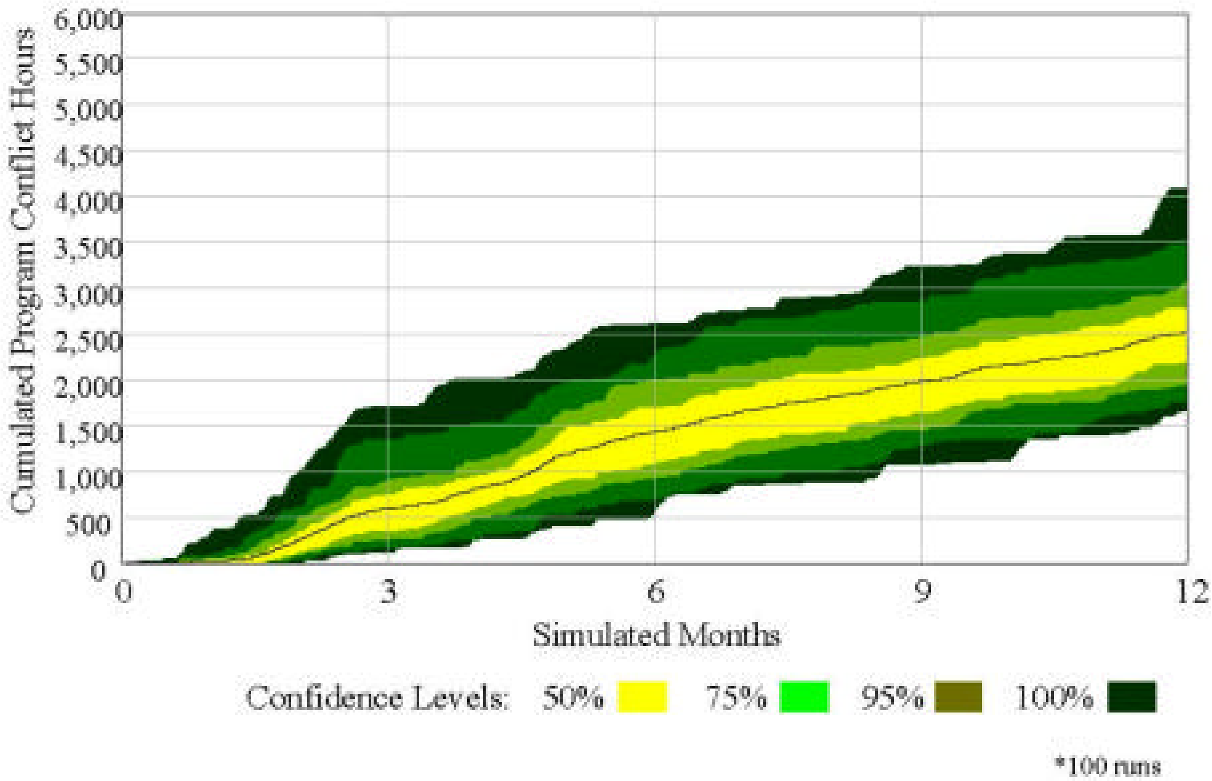

Figure 3.11: Cumulated Program Support Conflicted Time for FY01 (plot)

In addition to measuring the total amount of conflicted time, the model also keeps a record of the primary causes associated with the denial of range support. Another example of the conflicted program time is shown in Figure 3.12. This chart depicts the results from a single simulation of the model based on the FY01 launch manifest. It notes the amount of conflicted launch program hours for which each of the six identified categories was a contributing factor to the denial of required range support.

By closely examining Figure 3.12, one can see that a few of the plots cross over each other. This observation suggests that there may not be a decisive ranking of the relative impact of the six support conflict categories. In order to gain a better sense of the expected impact of each conflict category for FY01, a sensitivity analysis was deemed necessary.

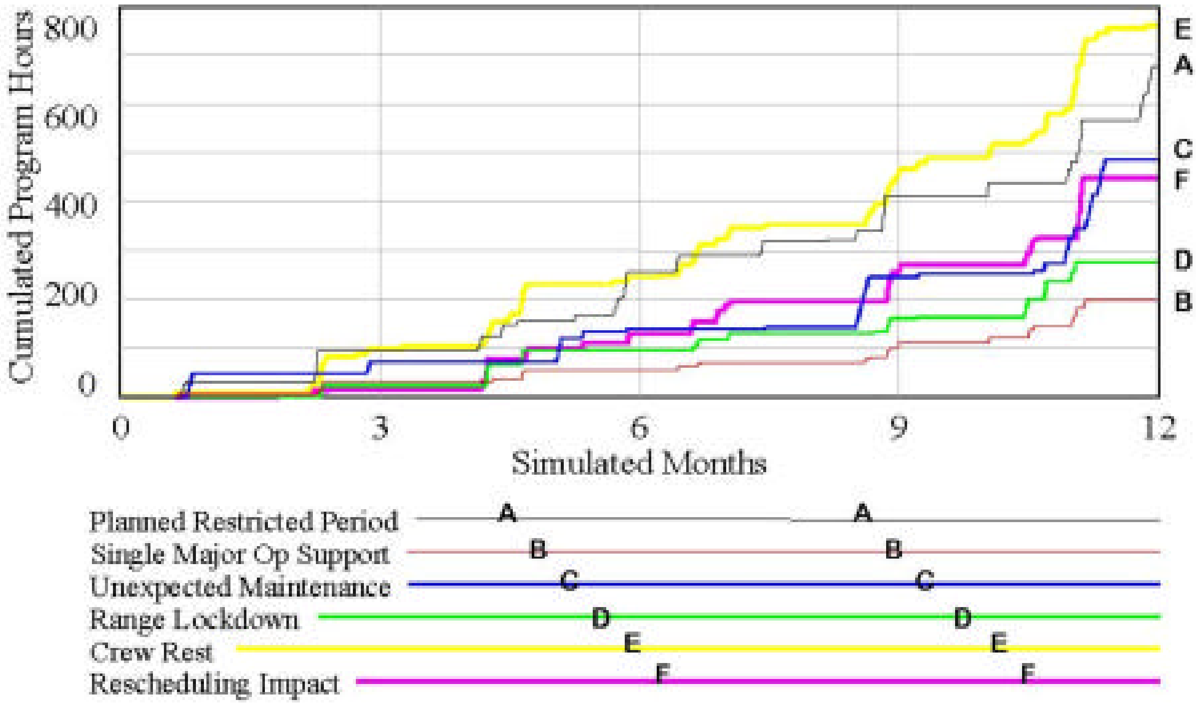

Figure 3.12: Cumulated & Categorized Conflict Time (plot)

The FY01 expected distribution of annual launch program support conflict hours is depicted in Figure 3.13 and is classified into categories. This chart reflects the results of one hundred simulations of the model. Confidence bounds are represented as various color bands, as indicated in the legend. Each of the six categories has a distribution of values where the central light-colored band notes the median 50% of the values produced during the sensitivity test. Similarly, the upper and lower dark bands correspond to values produced by the model, but at the outer regions of the distribution.

One observation from Figure 3.13 is that the complete distribution for each of the conflict categories covers a region of not less than 3 times the lowest value produced during the 100 simulations. This result is a gauge of the variability associated with these values. If only the average values for each category were presented, then no sense of category overlap or distribution would be possible. Therefore it would seem inappropriate to convey this behavior solely through average values.

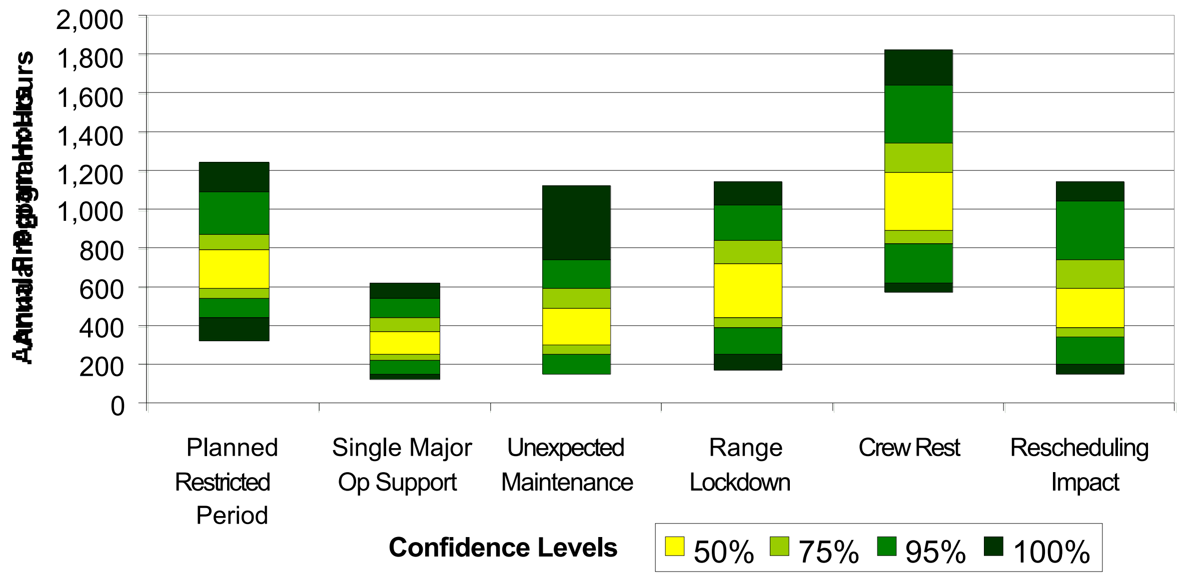

Figure 3.13: Expected Values of Support Conflict Time for FY01 (plot)

The underlying values used to produce Figure 3.13 could be used perform a cost benefit analysis based on launch program hours. They also provide the reader with a sense of the magnitude of time associated with range operations constraints. However, one should realize that these values are heavily dependent upon the number of launch programs operating on the range and the number of launch campaigns slated for the year. Modifications to either of these numerical assumptions could significantly alter the cumulated hours.

In order to provide a convenient means of comparing these results across different operating scenarios, a dimensionless form was created. Figure 3.14 presents the same data as in the previous chart, but in a dimensionless percentage format. This graph shows the expected % attribution of each of the support conflict categories to the overall amount of support conflict time.

An example of interpreting Figure 3.14 would be that a central value for the category ‘Planned Restricted Period’ is approximately 29%. This means that the category ‘Planned Restricted Period’ was a contributing factor during 29% of all the conflicted launch program time.

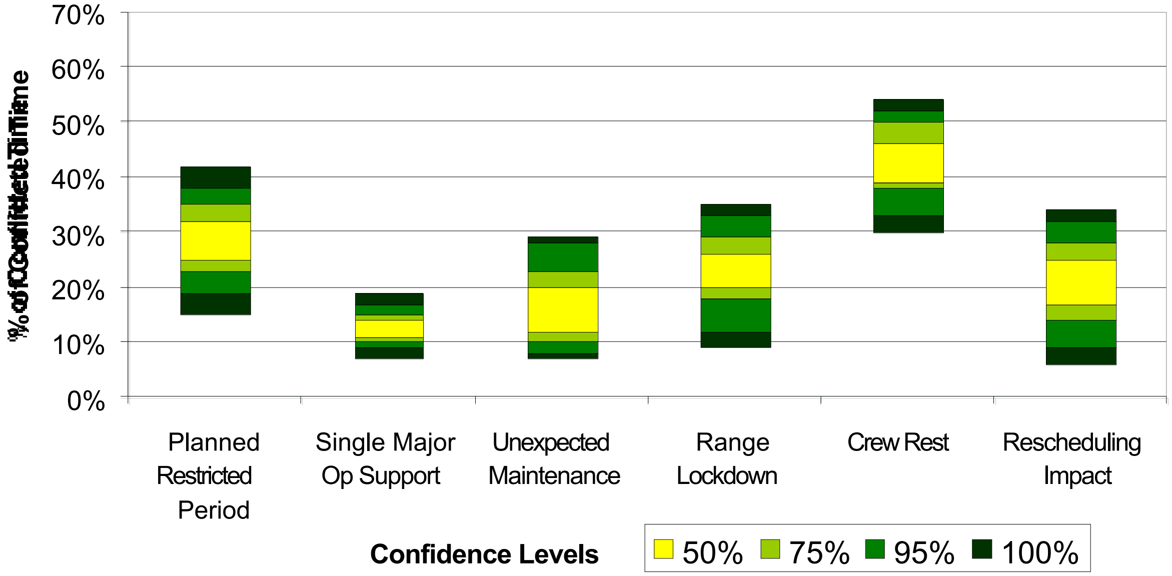

Figure 3.14: Expected % Attribution of Support Conflict Categories for FY01 (plot)

3.6.1.2 Consistency of Constraints Across Different Launch Programs in FY01?

The values of expected % attribution of each of the support conflict categories presented in Figure 3.14 are derived from the operations for all launch programs on the Eastern Range. The following series of figures addresses the question of whether these average Eastern Range values reflect the operations of the individual launch programs, or instead are merely averages of rather different program behaviors.

Values from three launch programs are used to compare specific launch program behavior to average Eastern Range behavior. These programs are identified as Launch Vehicle ‘A’, Launch Vehicle ‘B’, and Launch Vehicle ‘C’. Although the launch programs are not identified by actual program names, they were selected as a basis for comparison due to their relatively high rate of operations on the Eastern Range and the confidence level associated with their model input values.

A quick glance through the following six figures suggests that the average Eastern Range values of % attribution for each of the support conflict categories is reflective of the major individual launch programs for the FY01 scenario. This means that the relative constraints of range resources experienced by one launch program are similar to those experienced by most other programs.

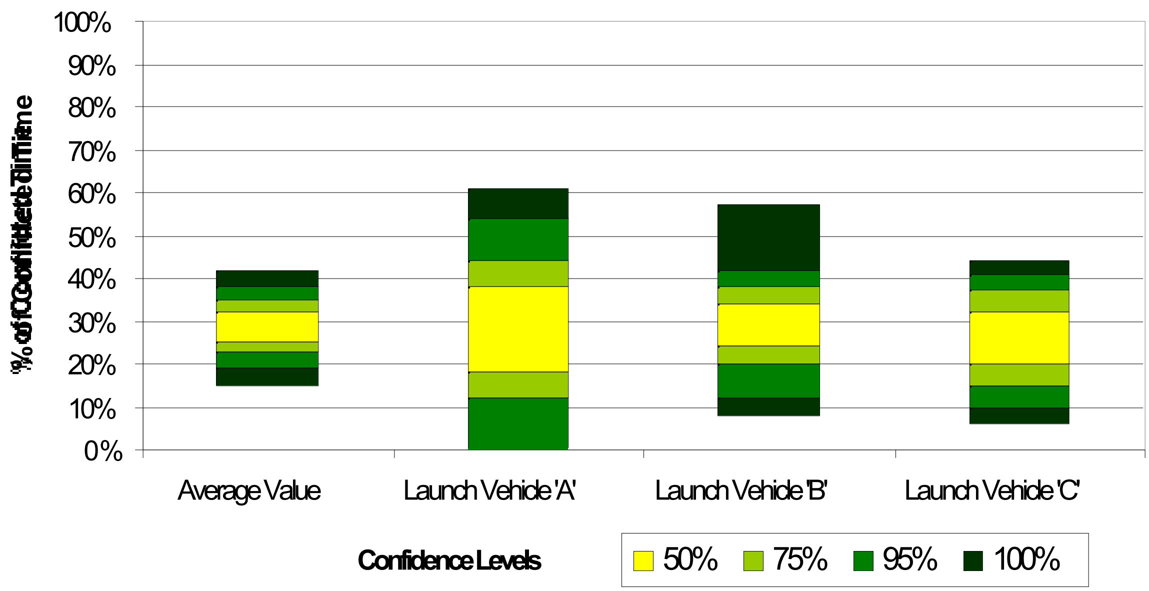

Figure 3.15: 'Planned Restricted Period' Consistency of Conflict Time % Attribution Across Programs for FY01 (plot)

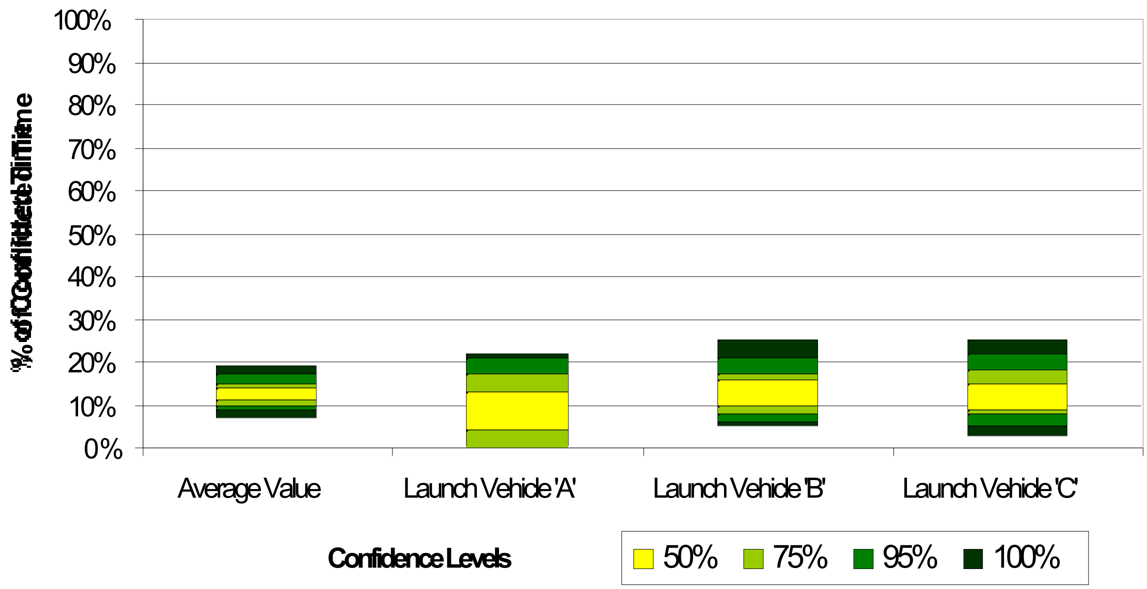

Figure 3.16: 'Single Major Op Support' Consistency of Conflict Time % Attribution Across Programs for FY01 (plot)

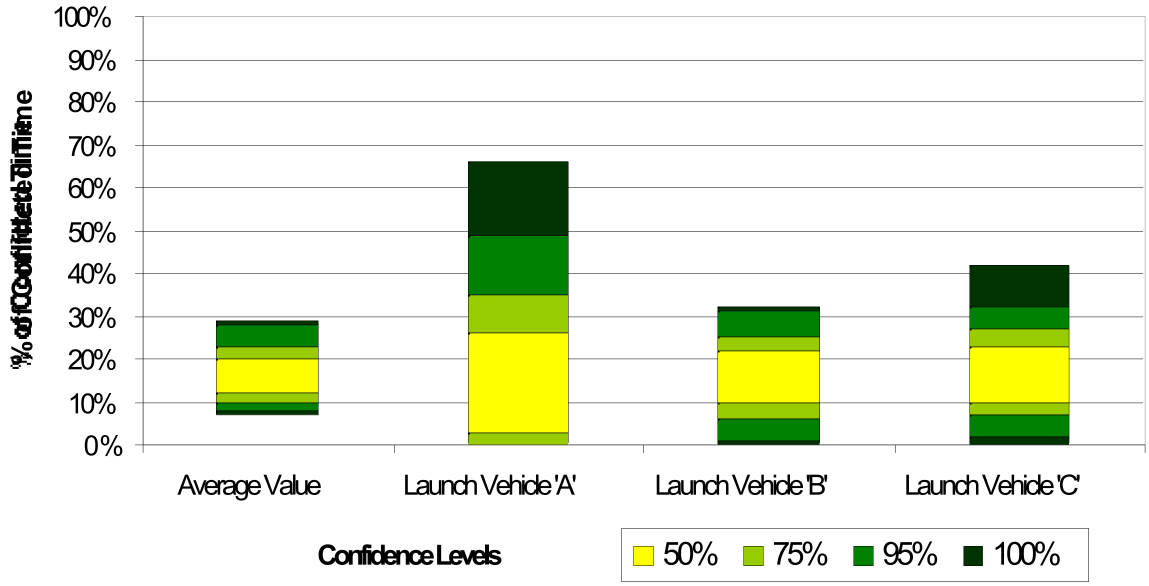

Figure 3.17: 'Unexpected Maintenance' Consistency of Conflict Time % Attribution Across Programs for FY01 (plot)

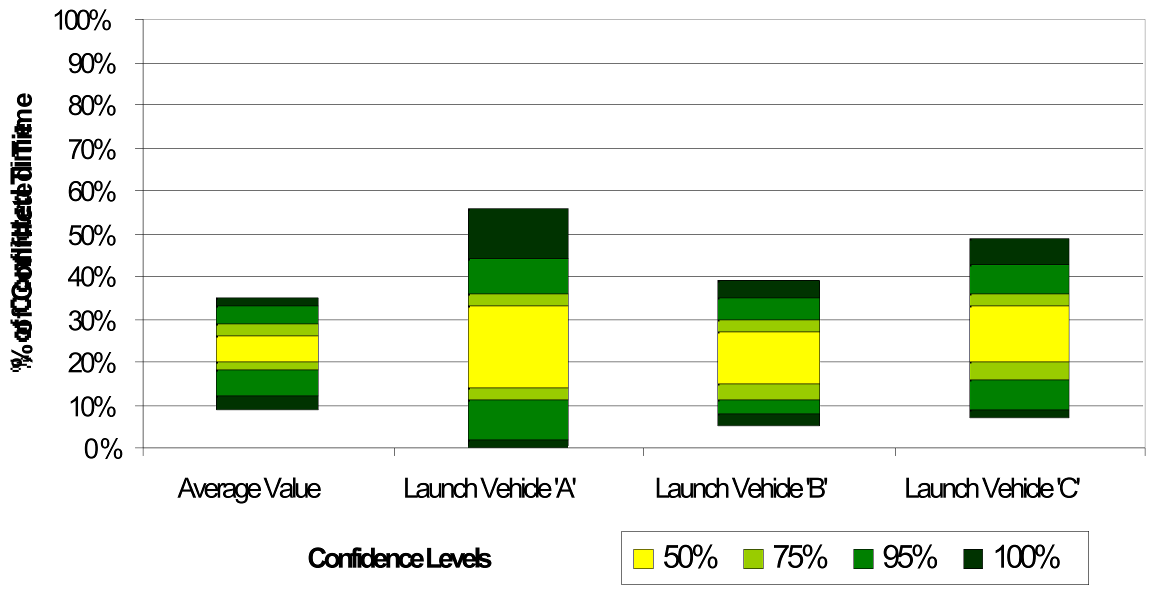

Figure 3.18: 'Range Lockdown' Consistency of Conflict Time % Attribution Across Programs for FY01 (plot)

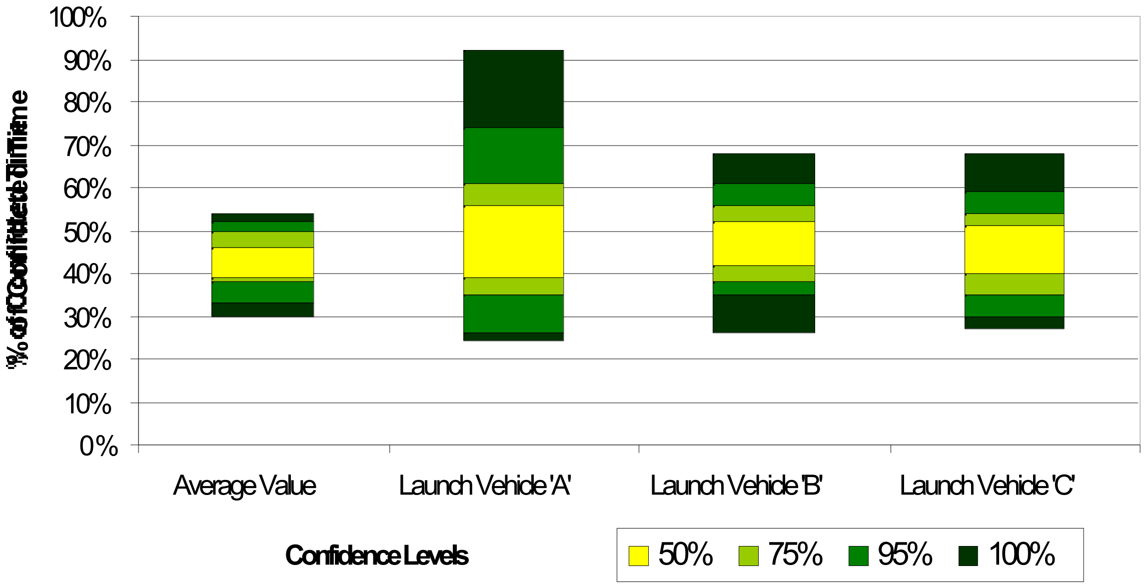

Figure 3.19: 'Crew Rest' Consistency of Conflict Time % Attribution Across Programs for FY01 (plot)

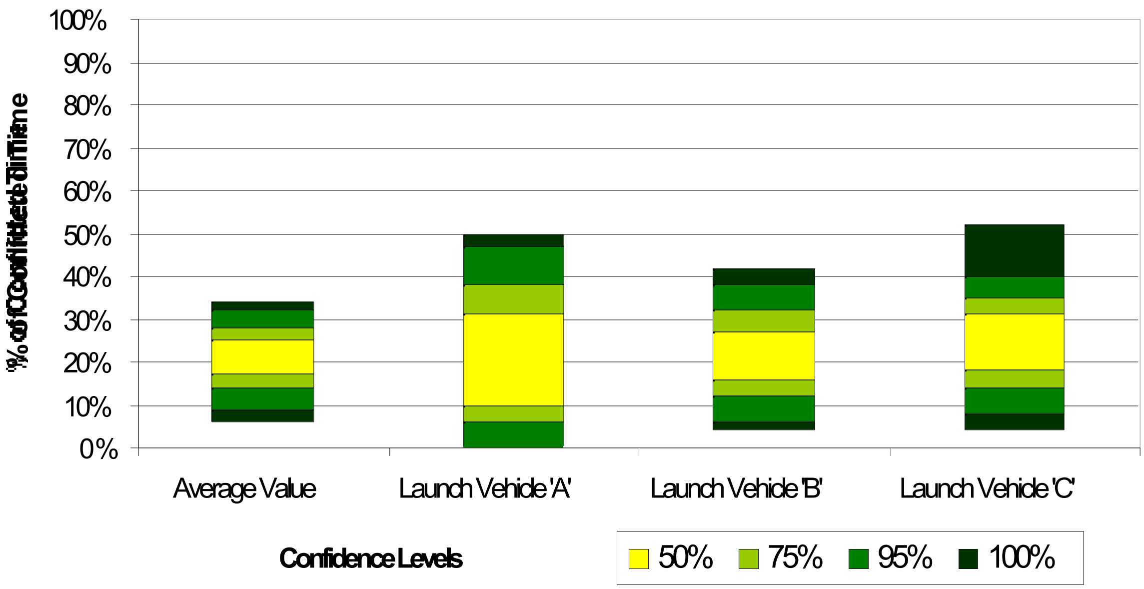

Figure 3.20: 'Rescheduling Impact' Consistency of Conflict Time % Attribution Across Programs for FY01 (plot)

3.6.1.3 Launch Program Delays

A launch program delay, in the context of this thesis, refers to the amount of time that a launch is set back from its initially scheduled date. Although a last minute weather condition may keep a launch vehicle on the ground for some extra time at the end of a launch campaign, other constraints such as the availability of range resources may have pushed the launch date back before the campaign was ever started. All launch delays, accounted for in the model, emanate from launch program support conflicted time periods (see Figure 3.11: Cumulated Program Support Conflicted Time for FY01 (plot)).

It is important to realize that the model was created with the intention of analyzing range-integrated launch capacity. This thesis is not an attempt to model the details of launch operations from a launch program perspective. In reality there are more sources of launch delays than those addressed in this focused research effort. For example, a spacecraft manufacturer may experience a delay in delivering the payload to the launch site for integration with the launch vehicle. In this case, the spacecraft delivery delay may be longer than the nominal spacecraft contingency delay time already planned for in the launch flow timeline. Depending upon the length of delay, this example might lie outside of the bounds of this thesis. If the delivery delay remained short, the launch program might be able to still launch on time. The model already covers this situation through the concept of operation flexibility. If the spacecraft delivery delay was long enough to warrant a reschedule of the launch date, then the situation would be covered through the 'Rescheduling Impact' category. On the other hand, if the delivery date was postponed for an extended period of time or if the mission was cancelled, then the situation would be classified as exceptional behavior. Exceptional behavior is viewed as outlying system behavior and is outside of the scope of this research effort.

The expected amount of launch program delay time for FY01 is depicted in Figure 3.21. This cumulated value of time is aggregated across all active launch programs. The mean value for the expected amount of launch program delay time during FY01 is projected to be just less than 2,000 hours and is noted as the central black plot. The range of values produced through 100 simulations of the model varied from approximately 1,300 hours to approximately 3,500 hours with varying degrees of associated probability. The corresponding confidence bounds are displayed in Figure 3.21.

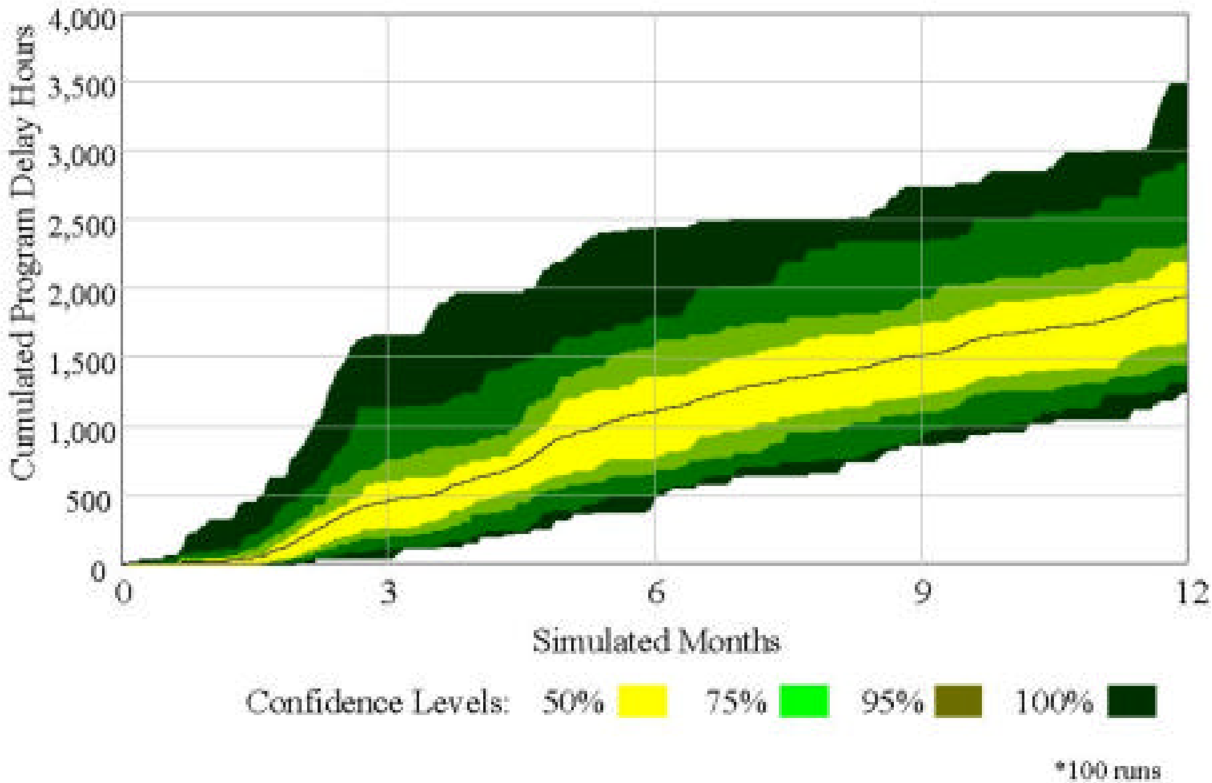

Figure 3.21: Cumulated Program Delay Time for FY01 (plot)

The capability of a launch program to conduct a specific operation at any one of multiple opportunities, due to the ability to work other tasks in parallel is referred to as operation flexibility. Possessing such flexibility allows a launch program to mitigate a portion of the potential launch delaying situations. Elimination of range dependence is one strategy used by launch programs to reduce susceptibility to launch delays. This approach is too extreme in some cases and operation flexibility is still widely used by launch programs operating from the Eastern Range in order to reduce the impact of launch delays.

Figure 3.22 presents the benefit of launch programs incorporating operational flexibility into their launch flows. Based on running one hundred simulations of the model for the FY01 Eastern Range launch manifest, it was determined that roughly 1/4th of all potential launch-delaying time is mitigated through operational flexibility.

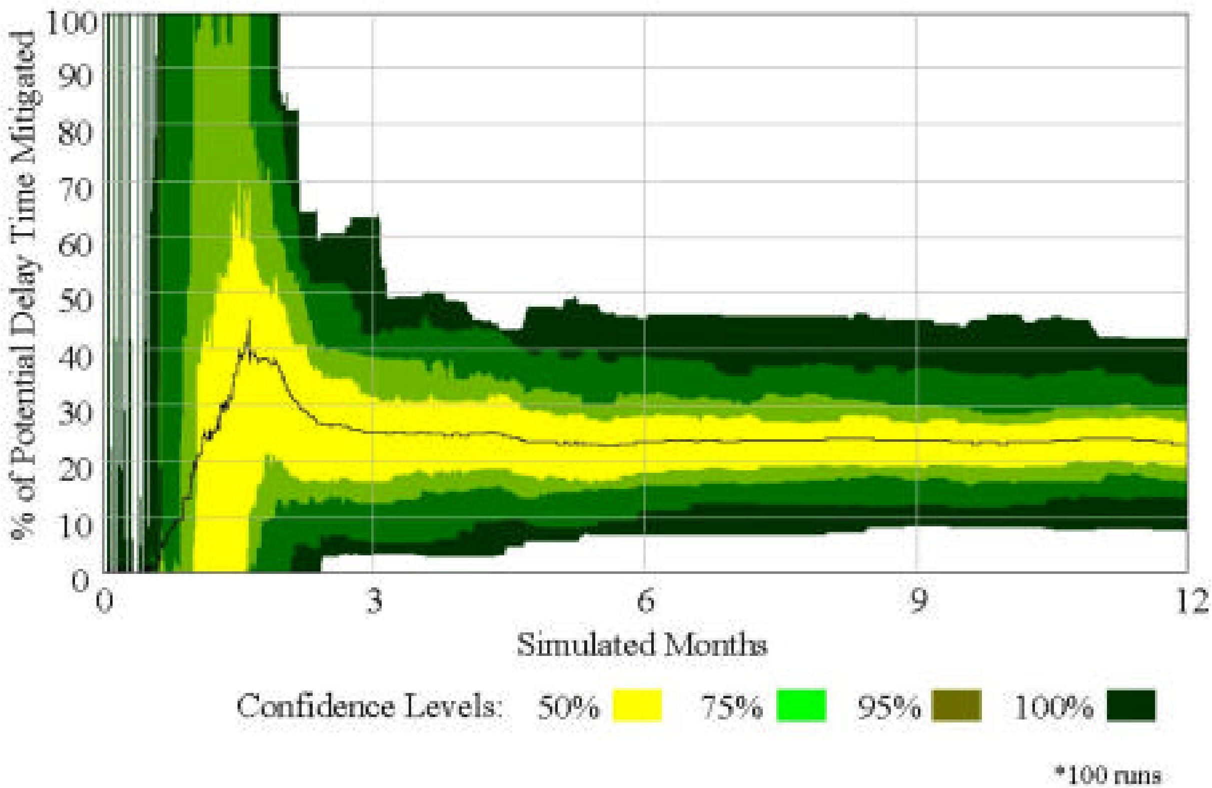

Figure 3.22: Potential Delay Time Mitigated by 'Operation Flexibility' for FY01 (plot)

3.6.2 Capacity Operating Conditions for FY01

The word "capacity" is well understood by most individuals, but it has multiple meanings. Selected definitions relevant to this work, from the *American Heritage Dictionary of the English Language*, include: **1.** The ability to receive, hold, or absorb. **2.** A measure of this ability. **3.** The maximum or optimum amount. **4.** The ability to do something.

When trying to determine the launch capacity of the U.S. Eastern Range, it is important to first define the context within which the word "capacity" is being used. Otherwise others will almost certainly misinterpret the results and may even use them without understanding the implicit assumptions used to generate such values.

Within this thesis, launch capacity is measured in terms of the number of launches that may be conducted from the Eastern Range during the course of a single year. One possible drawback to such a metric is that cost, time, and mass (i.e. energy) are not directly reflected by this measure. For instance, compare the resources necessary to prepare and launch a Titan IV launch vehicle to those of a Space Shuttle or a Pegasus launch vehicle. Realizing this, one should determine whether or not using such a measure of capacity is appropriate for the analysis at hand.

Another consideration when using the word "capacity" is to realize what operating conditions frame the environment in which "capacity" is being defined. For example, consider the following four scenarios of annual Eastern Range launch capacity. Each is a valid interpretation, which leads to four unique measures of the launch capacity concept.

1. **Independent Launch Capacity**- considers the maximum number of launches which may be conducted from each launch pad, or independent launch facility utilizing a range, based solely on launch program throughput capability without regard to the integration of any range support requirements or restrictions

2. **Supplied Launch Capacity**- considers the maximum number of launches which may be supported by the range system without regard to the throughput capability of each launch pad, or independent launch facility utilizing the range

3. **Exclusive Vehicle Launch Capacity**- considers the maximum number of launches of a specific vehicle type, using specified launch facilities, which may be conducted, assuming this was the only launch activity taking place, while taking into account the integration of range support requirements and restrictions

4. **Competed Launch Capacity**- considers the maximum number of launches which may be conducted from a collection of launch pads, or independent launch facilities, utilizing a range, based not only on launch program throughput capability but also the simultaneous integration of range support requirements and restrictions

The predominant version of capacity used in the analysis section of this thesis is “Competed Launch Capacity”. Modeling this final interpretation requires the highest level of fidelity, but arguably is the most realistic and worthwhile measure of launch capacity from the four suggested choices. The following section uses the generic terms “Range Capacity” or “Launch Capacity” with an implicit reference to “Competed Launch Capacity” unless noted as otherwise.

Figure 3.23 depicts results from one hundred simulations of the model operating under a range capacity scenario for FY01. This graph shows a step plot of the expected number of cumulated launches throughout the course of the year (see Figure 3.9: Cumulated Launches for FY01 (plot) for scenario comparison). The mean value of these simulations is fairly linear and is represented as the central light-colored line.

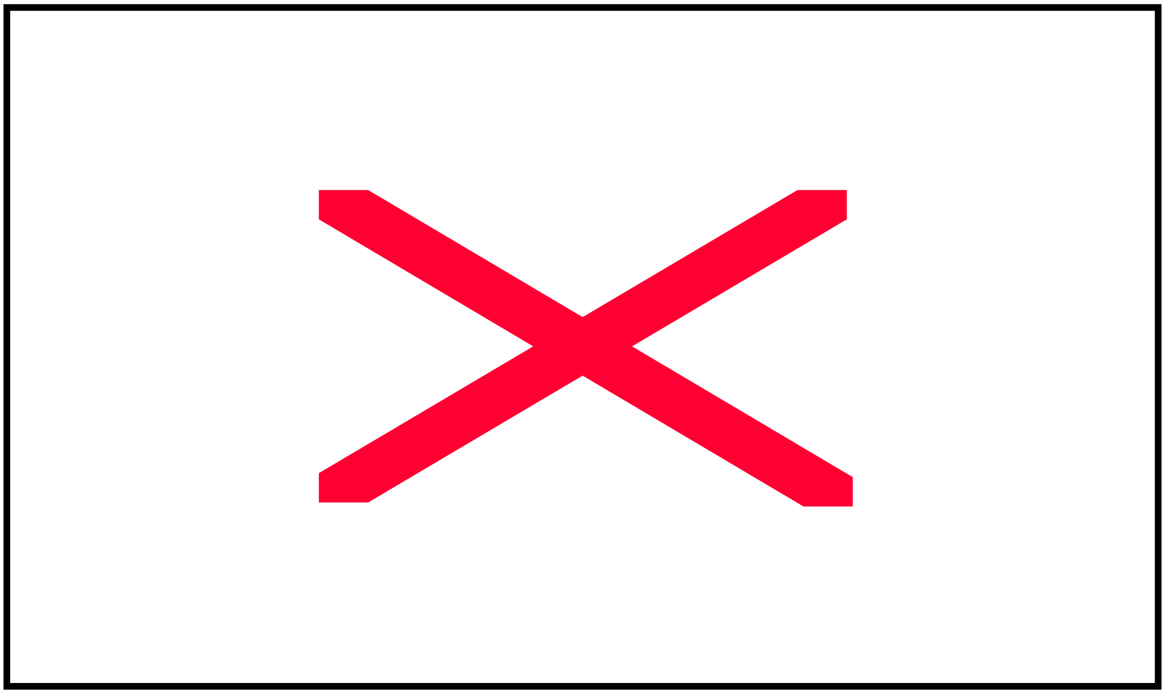

Figure 3.23: Launch Capacity for FY01 (plot)

The U.S. Eastern Range expected launch capacity for FY01 was determined to be a distribution of values. The distribution is presented in Figure 3.24 and is measured as a probability of occurrence. The average expected value was calculated to be 51 launches and the distribution had upper and lower bounds of 54 and 49 launches respectively.

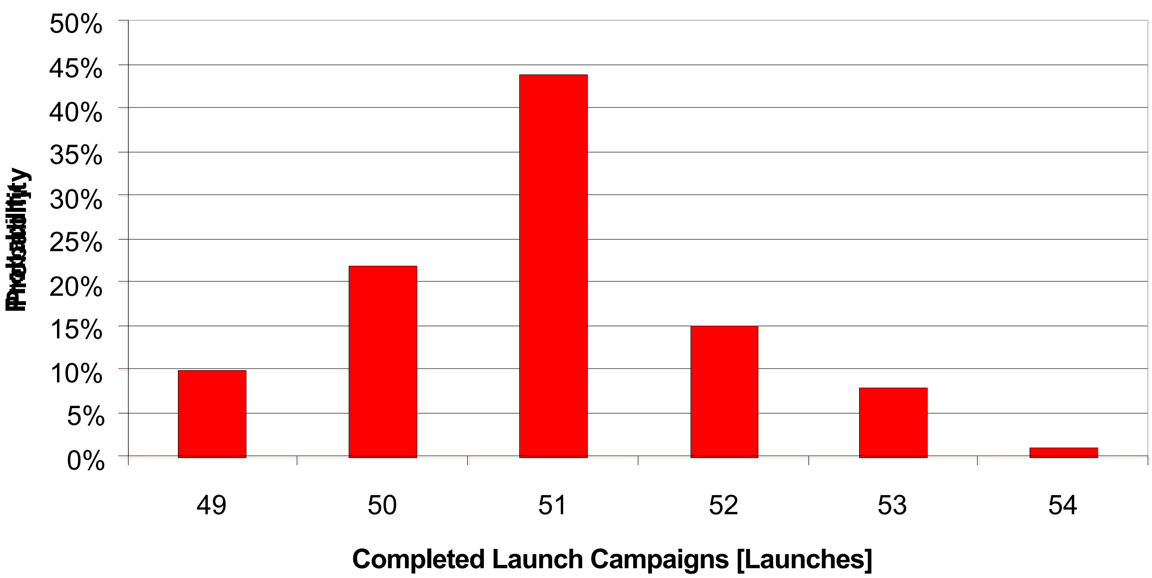

Figure 3.24: Launch Capacity Distribution for FY01 (plot)

Figure 3.25 depicts a subset of the launches from the capacity scenario. This figure shows the cumulated launches of a single type of launch vehicle, identified as Vehicle ‘X’. The clustering effect of 2 launches cumulating at about the same time is due to a combination of two factors. The first factor is the existence of 2 launch pads for this type of launch vehicle. The second factor arises from the same simplification used to model the launch vehicle operations in the current version of the model, as discussed for Figure 3.9.

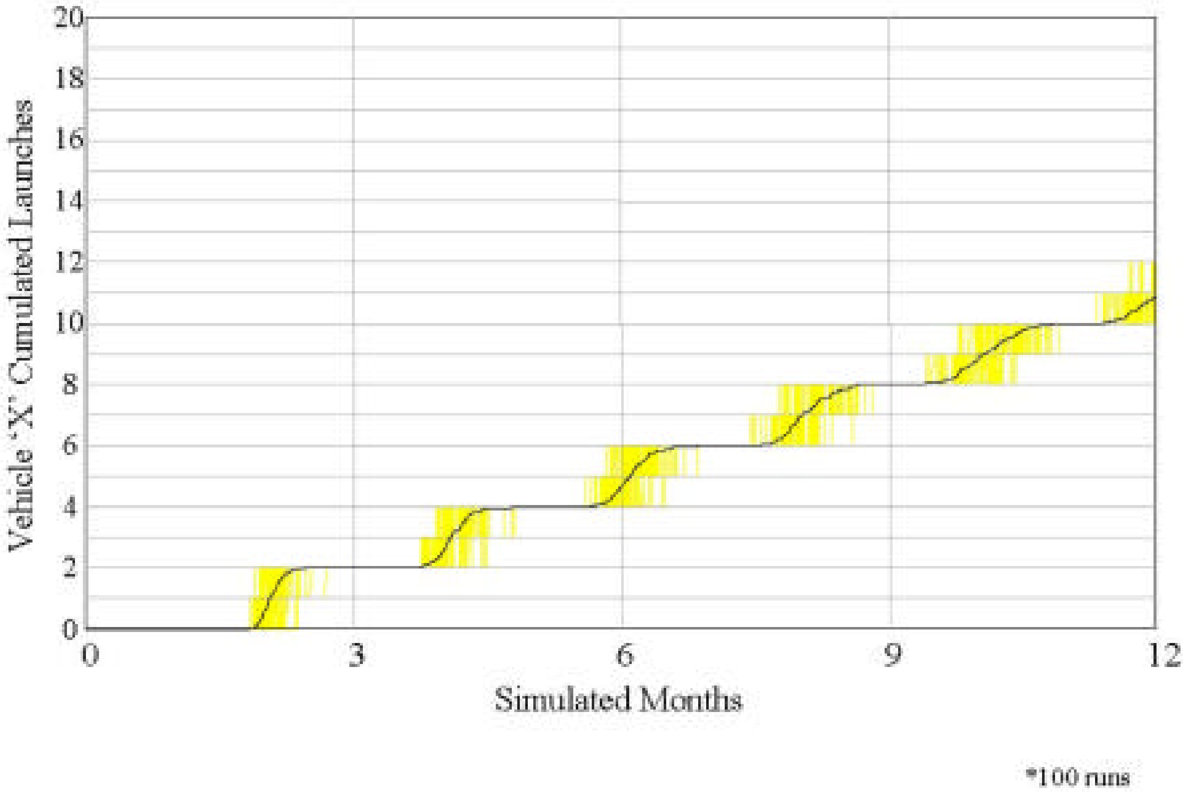

Figure 3.25: Vehicle 'X' Cumulated Launches for FY01 Range Capacity Scenario (plot)

In comparison, Figure 3.26 shows the expected cumulated launches for vehicle ‘X’ under the scenario of “Exclusive Vehicle Launch Capacity”. Two observations are presented in regards to both figures.

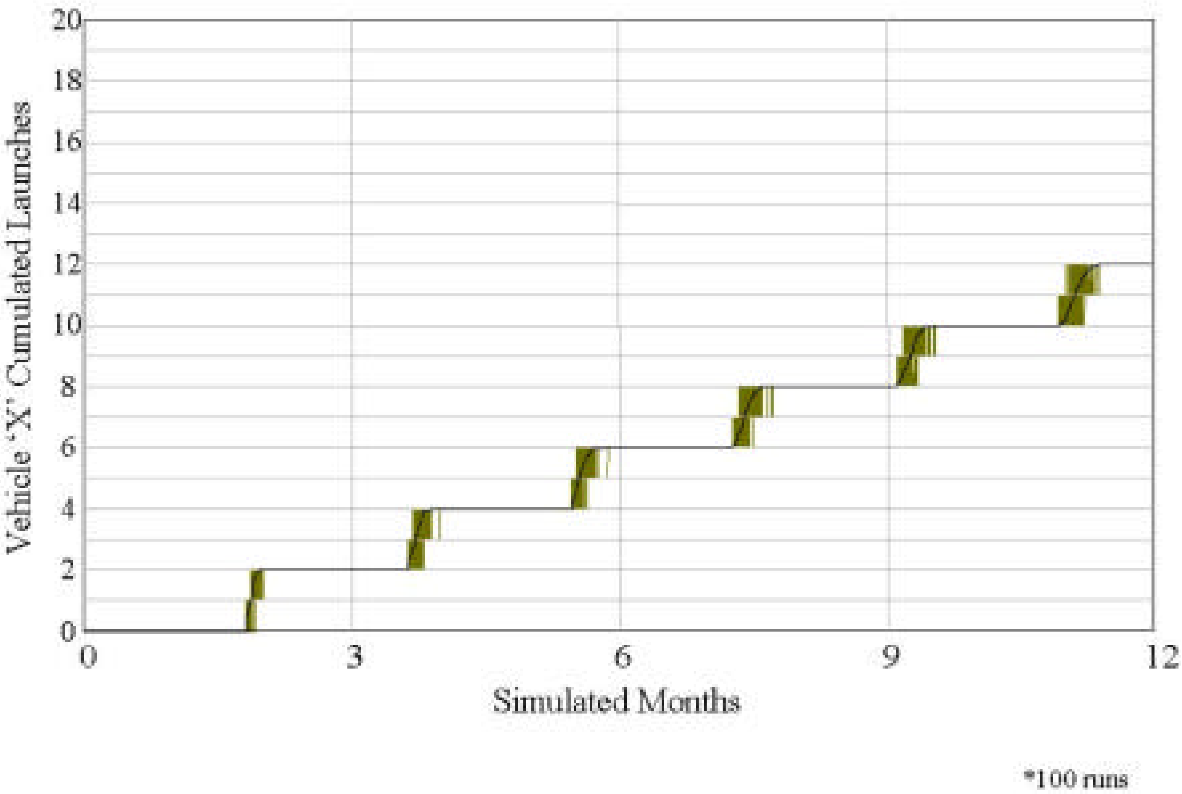

Figure 3.26: Vehicle 'X' Cumulated Launches for FY01 Exclusively Vehicle 'X' Capacity Scenario (plot)

As expected, the model confirms that there is a higher amount of launch date uncertainty associated with increased range congestion levels. This can be seen by noting how the width of each band at each cumulated step of the one hundred plots is narrower in Figure 3.26 than in Figure 3.25.

A second observation is that for a specific vehicle type a lower amount of range congestion will result in a higher launch rate. This can be interpreted as having either an increased capability to launch additional vehicles within a set amount of time or launching a set number of vehicles in a shorter amount of time.

The launch vehicle impact time due to range congestion is shown for three unidentified types of launch vehicles in Figure 3.27. These values represent the difference in time when the final launch occurred for each program during the competed launch capacity scenario versus when this launch occurred in the exclusive vehicle launch capacity scenario. Those launch vehicle types included in Figure 3.27, which operate at multiple launch pads, reflect aggregated values from all associated launch pads. Under the range capacity scenario, in FY01 the congestion on the range would potentially impact various launch vehicles by 24, 50, and 66 calendar days.

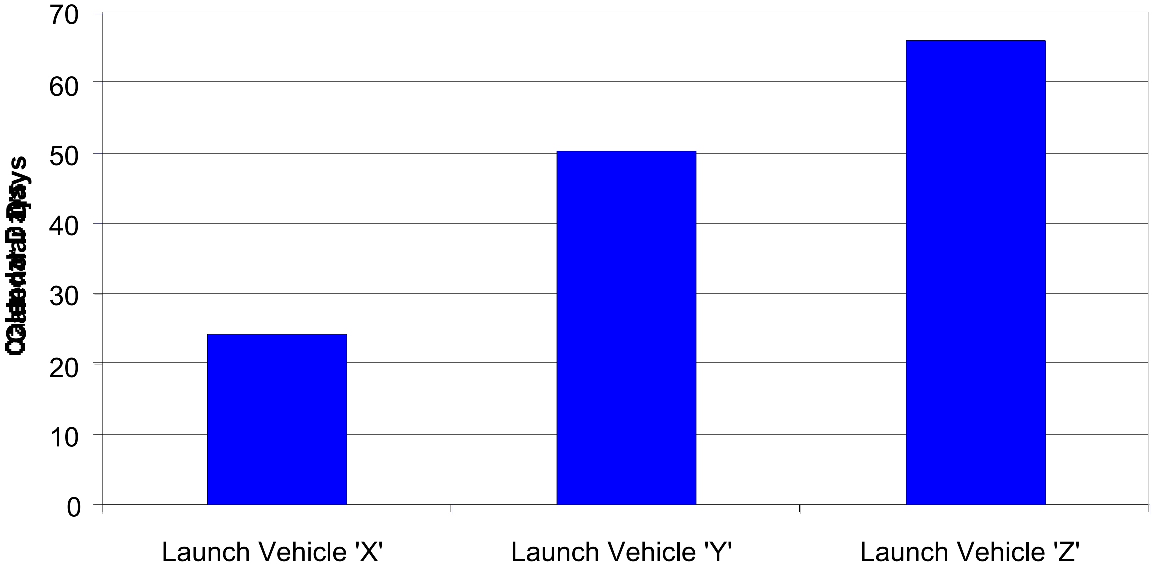

Figure 3.27: Time Impact of Range Congestion on Launch Vehicle Types at Capacity Conditions for FY01 (plot)

Figure 3.28 compares the expected number of completed launch campaigns for three different scenarios. In this analysis the number of launches is expressed as a percentage. The percentage is calculated as the number of launches in the scenario of interest divided by the number of launches for the same vehicle(s) from the independent launch capacity scenario. Therefore, each of the four vehicle groups has a value of 100% for the independent launch capacity scenario, which is not included in the chart.

The launch vehicle group ‘Eastern Range Launch Vehicles’ represents all of the launch vehicle activity. This category is omitted from the first scenario of Figure 3.28, labeled as ‘Exclusive Vehicle Potential Campaigns’ because this concept has no meaning. A sense of the expected launch operations rate for FY01 can be drawn by comparing values between the final two categories of Figure 3.28. This chart suggests that the overall FY01 launch manifest does not particularly utilize the capacity of the range. However, if one compares the different launch vehicles across these final two scenarios, then it can be said that Launch Vehicle ‘C’ has a relatively busy schedule compared to Launch Vehicle ‘B’. Launch Vehicle ‘A’ has the least active schedule relative to its own capability to launch.

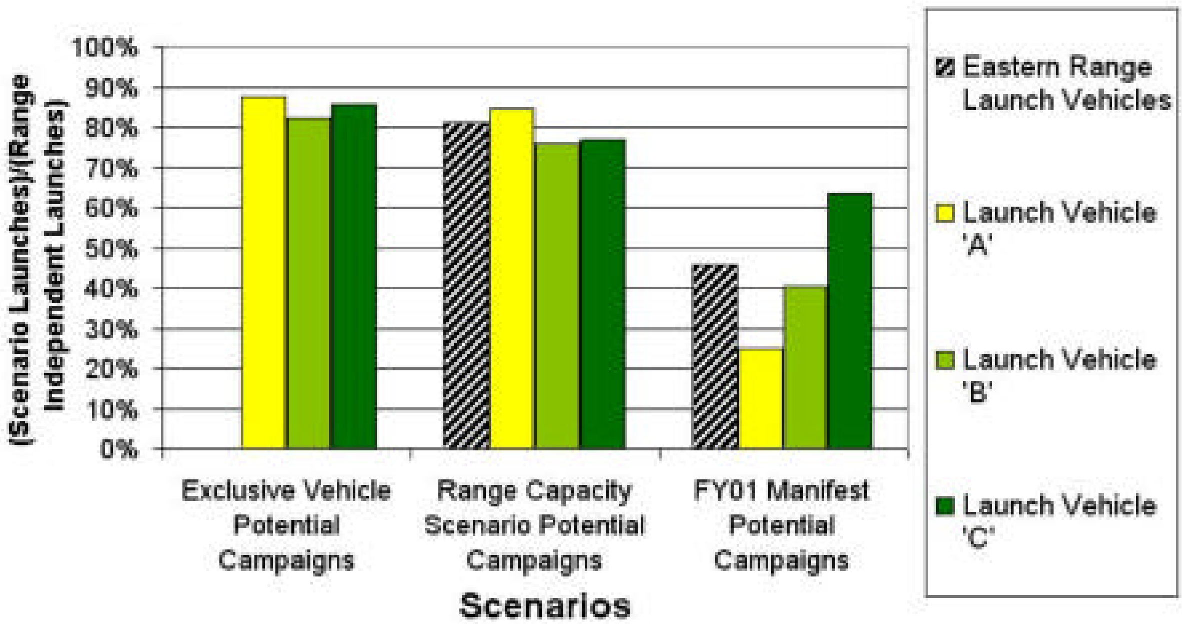

Figure 3.28: Launch Capacity Categories for FY01 (plot)

3.6.2.1 Range Support Conflicts for FY01 Capacity Scenario

Analogous to the analysis performed for the FY01 launch manifest scenario in section 3.6.1.1 of this thesis, the following analysis corresponds to a scenario of range capacity conditions for FY01. Figure 3.29 depicts sensitivity values for the cumulated amount of launch program conflicted time. The model predicts that under capacity conditions, there would be an average of almost 10,000 total program hours when range support was denied to launch programs. This value is roughly 4 times as high as the actual value expected for FY01 based on the launch manifest as depicted in Figure 3.11. The range of values produced through 100 capacity simulations of the model varied from approximately 8,000 hours to around 12,000 hours with varying degrees of associated probability.

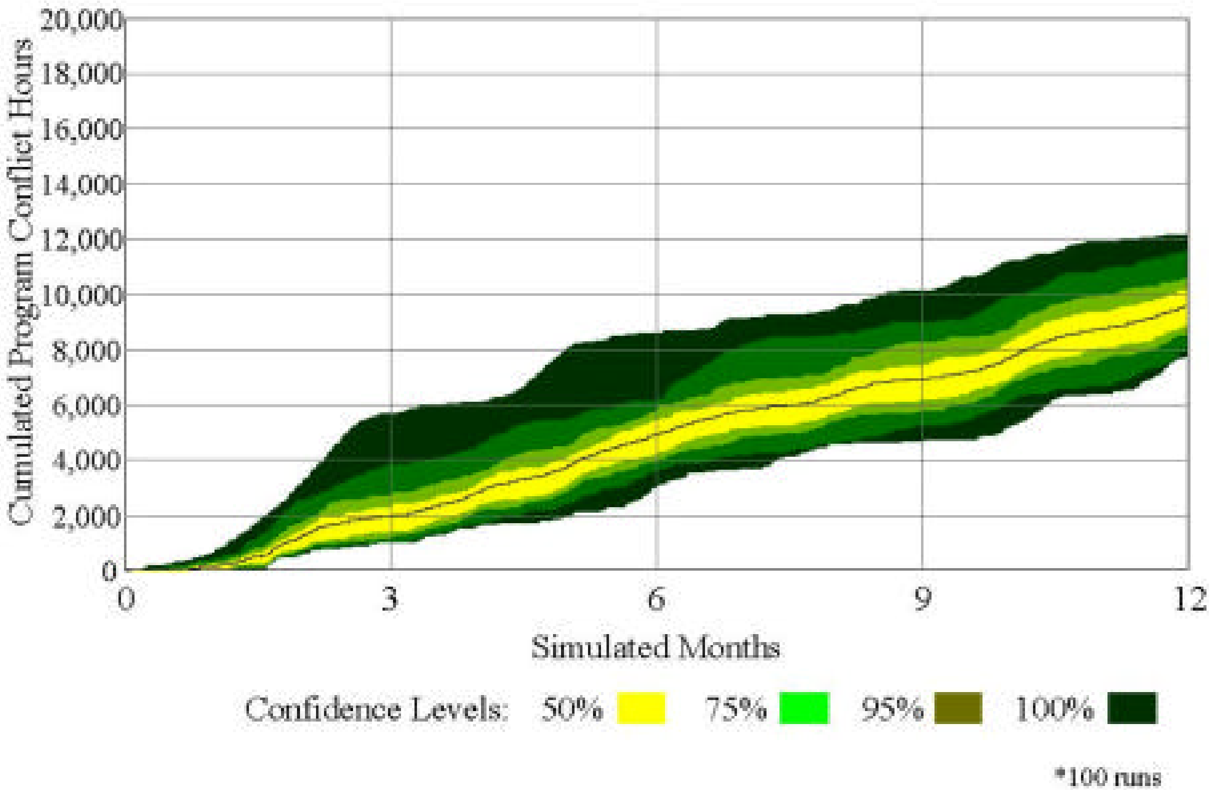

Figure 3.29: Cumulated Program Support Conflicted Time for FY01 Capacity Scenario (plot)

The expected distribution of annual launch program support conflict hours for the FY01 range capacity scenario is depicted in Figure 3.30. As with previous analyses, this chart reflects the results of one hundred simulations of the model. Confidence bounds are represented as various color bands, as indicated in the legend. Each of the six categories has a distribution of values where the central light-colored band notes the median 50% of the values produced during the sensitivity test. Similarly, the upper and lower dark bands correspond to values produced by the model, but at the outer regions of the distribution. Following this chart, the expected % attribution of each of the six support conflict categories is presented in Figure 3.31 for the FY01 capacity scenario.

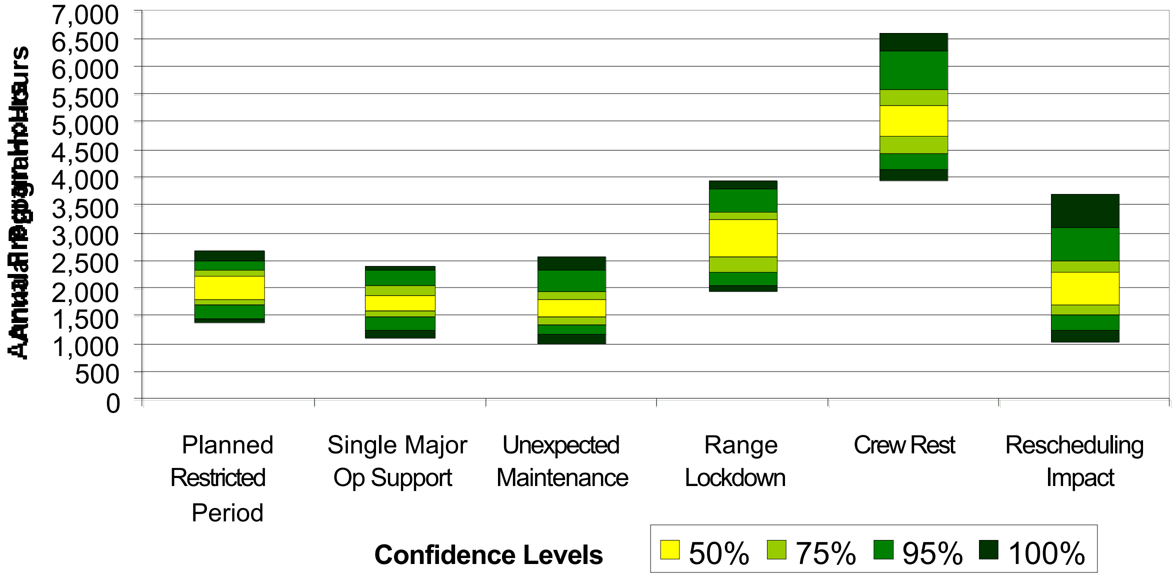

Figure 3.30: Expected Values of Support Conflict Time for FY01 Capacity Scenario (plot)

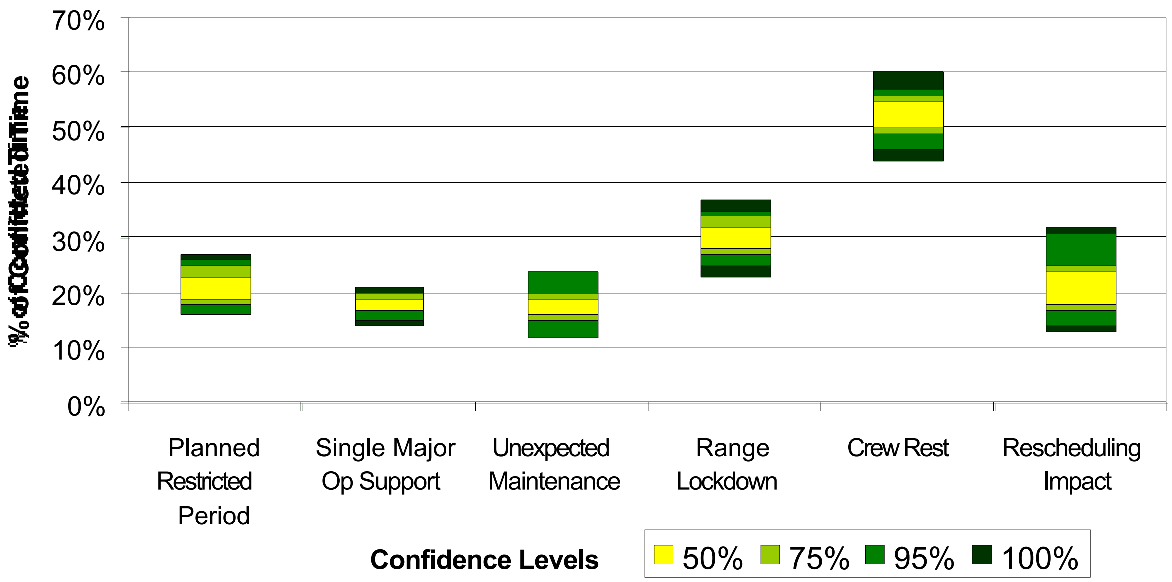

Figure 3.31: Expected % Attribution of Support Conflict Categories for FY01 Capacity Scenario (plot)

3.6.2.2 Consistency of Constraints Across Different Launch Programs for the FY01 Range Capacity Scenario?

As conducted for the expected operating conditions of the range for FY01, the following series of graphs are used to determine whether the distributions of conflict hours for the range as a whole reflect the constraints experienced by individual launch programs. The programs labeled Launch Vehicle ‘A’, Launch Vehicle ‘B’, and Launch Vehicle ‘C’ remain as the same programs used in the previous analysis.

As during the FY01 expected operating scenario, the following six figures suggest that the average Eastern Range values of % attribution for each of the support conflict categories is reflective of the major individual launch programs for the FY01 range capacity scenario. This means that the relative constraints of range resources experienced by one launch program are similar to those experienced by most other programs.

One observation from comparing both sets of graphs from each of the two FY01 operating scenarios is that the distributions for all of the categories of the capacity scenario are tighter than those of the expected FY01 operating scenario. This effect is thought to be the result of an increase of operations regularity associated with operating at capacity conditions. Such an increase in regularity would tend to reduce the uncertainty of predicting values for range support constraints.

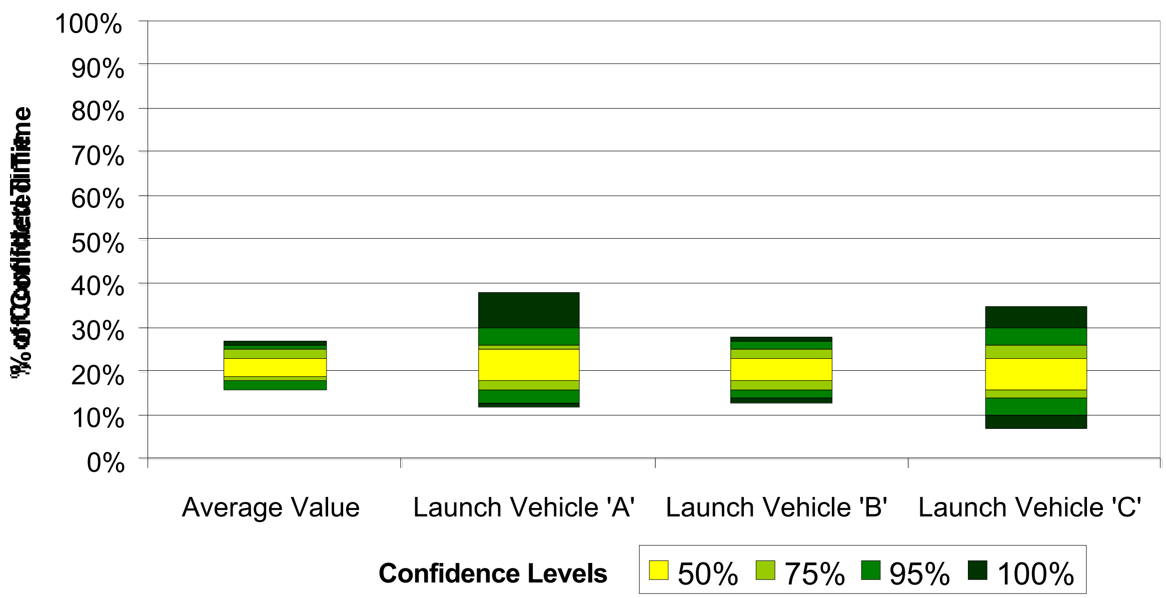

Figure 3.32: 'Planned Restricted Period' Consistency of Conflict Time % Attribution Across Programs for FY01 Capacity Scenario (plot)

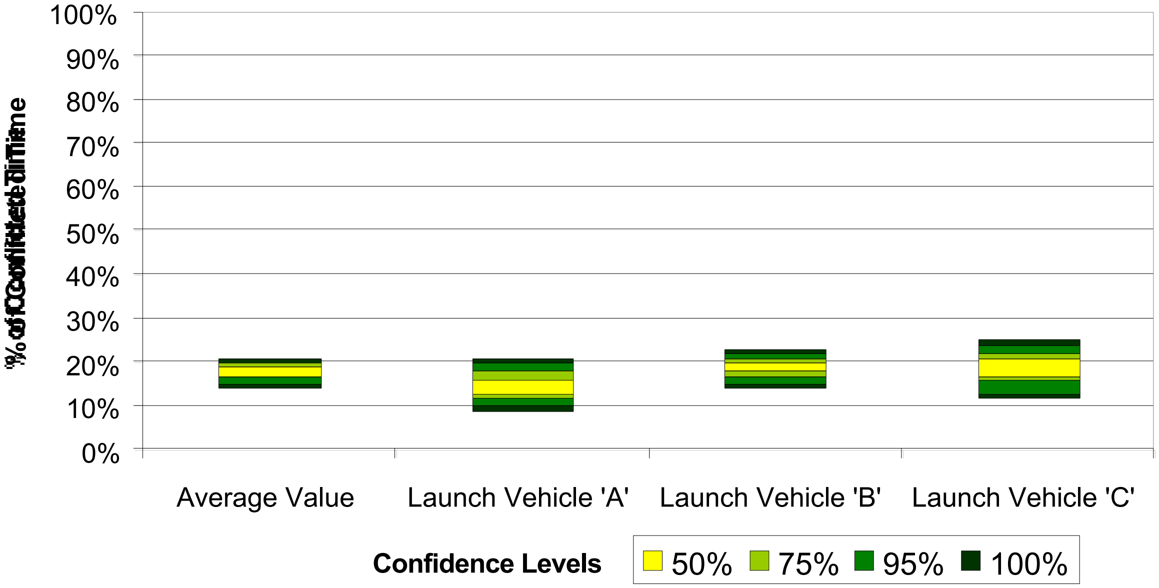

Figure 3.33: 'Single Major Op Support' Consistency of Conflict Time % Attribution Across Programs for FY01 Capacity Scenario (plot)

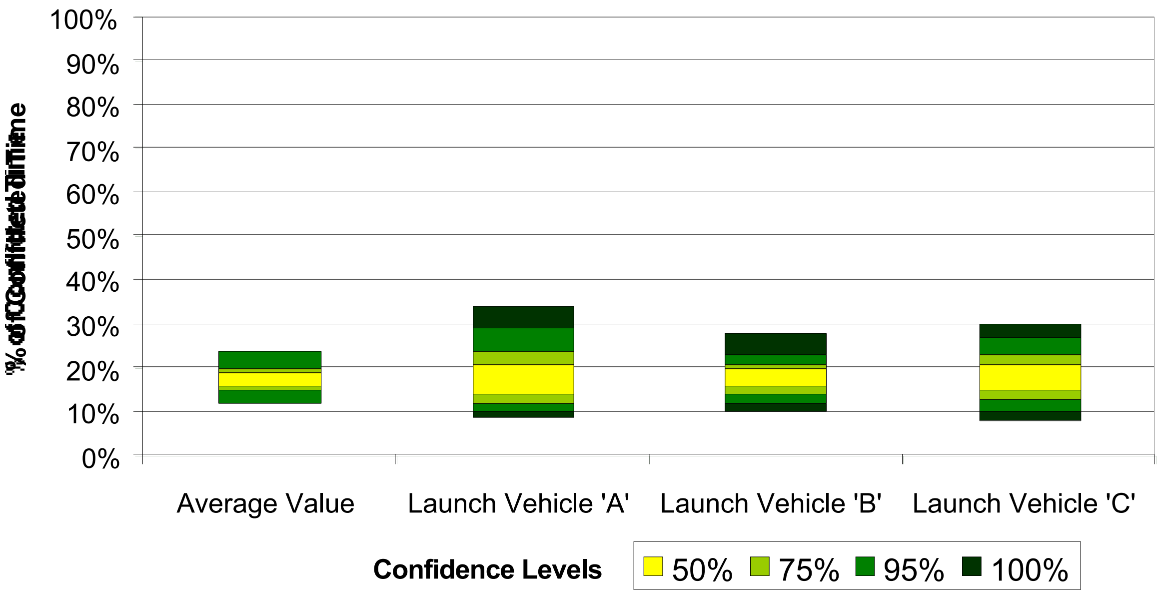

Figure 3.34: 'Unexpected Maintenance' Consistency of Conflict Time % Attribution Across Programs for FY01 Capacity Scenario (plot)

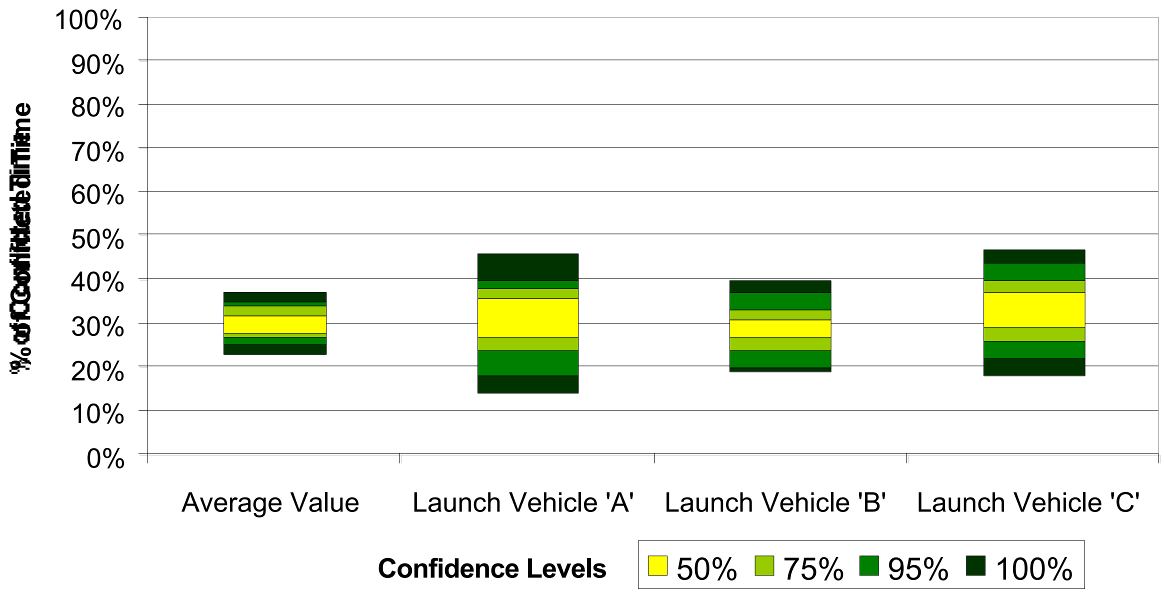

Figure 3.35: 'Range Lockdown' Consistency of Conflict Time % Attribution Across Programs for FY01 Capacity Scenario (plot)

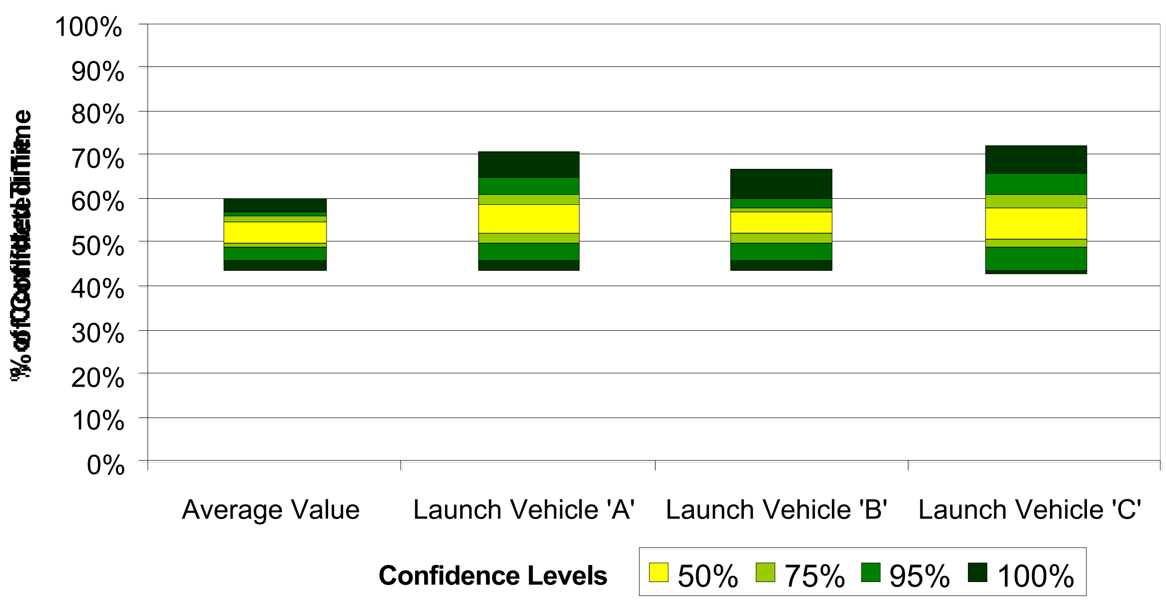

Figure 3.36: 'Crew Rest' Consistency of Conflict Time % Attribution Across Programs for FY01 Capacity Scenario (plot)

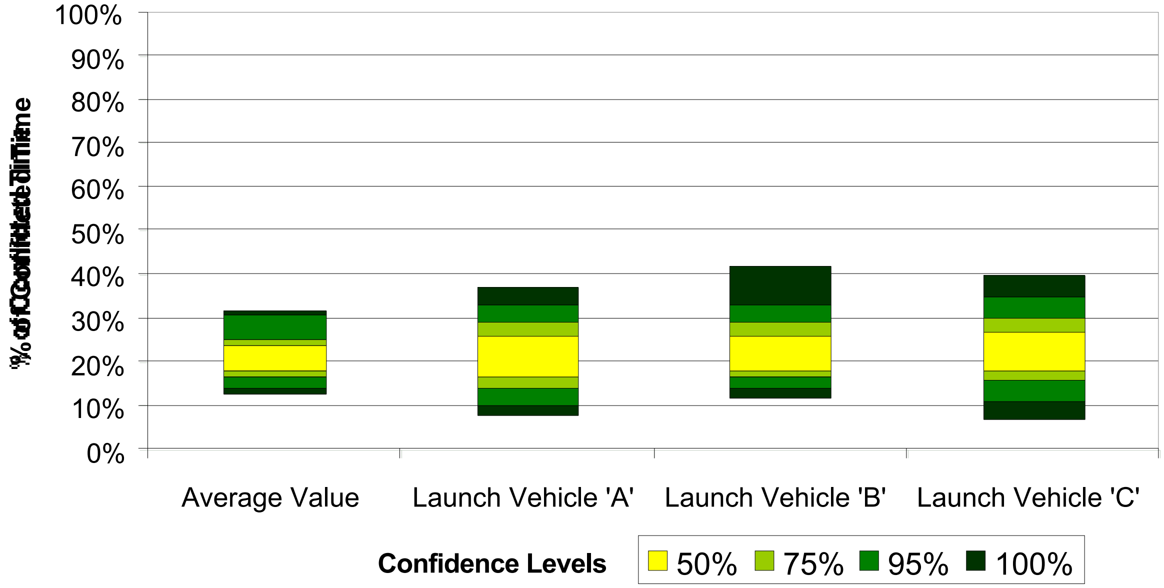

Figure 3.37: 'Rescheduling Impact' Consistency of Conflict Time % Attribution Across Programs for FY01 Capacity Scenario (plot)

3.6.2.3 Launch Program Delays During the Scenario of Range Capacity Conditions for FY01

The amount of launch program delay expected for FY01 capacity conditions is depicted in Figure 3.38. This analysis was performed in a similar fashion to the earlier launch delay analysis for the expected operating conditions in FY01 as described in thesis section 3.6.1.3. The resulting cumulated value of time is aggregated across all active launch programs. The mean value for the expected amount of launch program delay time during the FY01 capacity scenario was projected to be around 7,700 hours and is noted as the central black plot. This value is roughly four times as high as the mean value projected for the expected operating conditions for FY01. The range of values produced through 100 simulations of the scenario was found to begin at approximately 6,000 hours and went to just over 10,000 hours with varying degrees of associated probability. The corresponding confidence bounds are displayed in Figure 3.38.

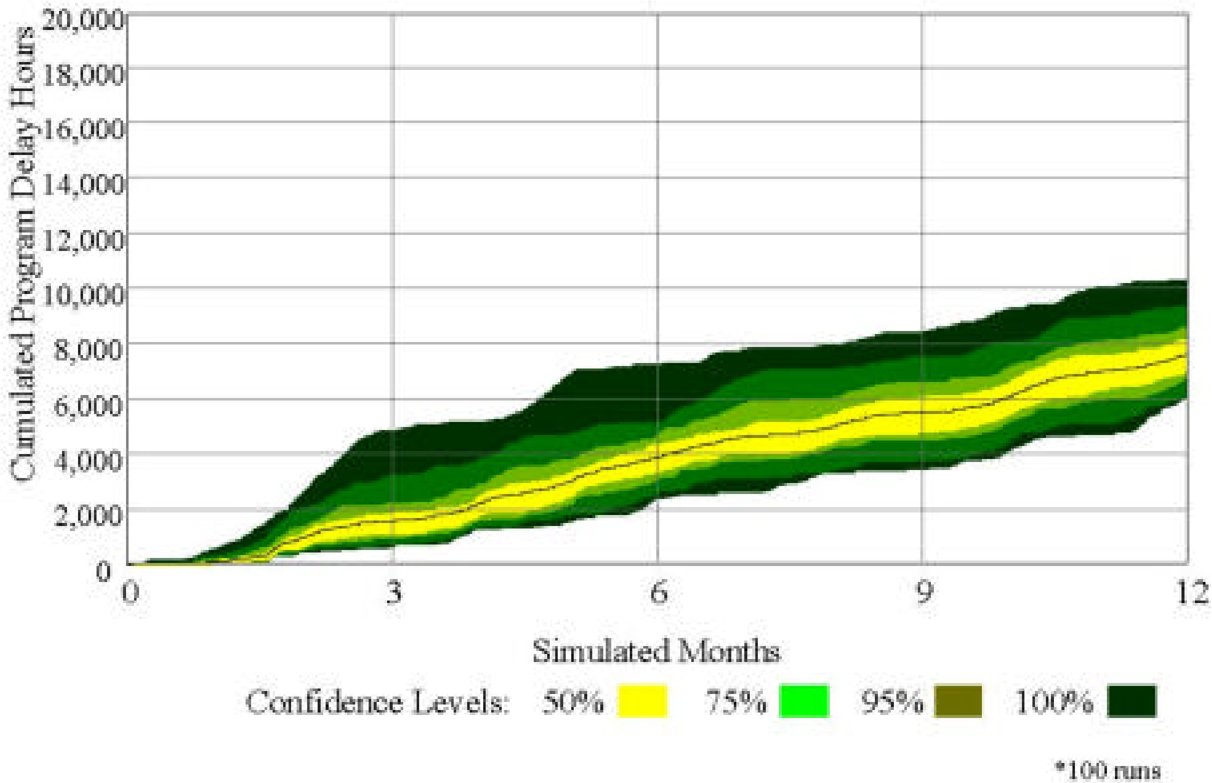

Figure 3.38: Cumulated Program Delay Time for FY01 Capacity Scenario (plot)

3.6.3 Comparing Range Support Constraints Between Expected Conditions and Range Capacity Conditions for FY01

The average cumulated program conflict hours for the scenario of expected FY01 operating conditions as well as the FY01 range capacity scenario are shown in Figure 3.39. These values represent mean values resulting from one hundred model simulations for each of the two U.S. Eastern Range FY01 operating scenarios.

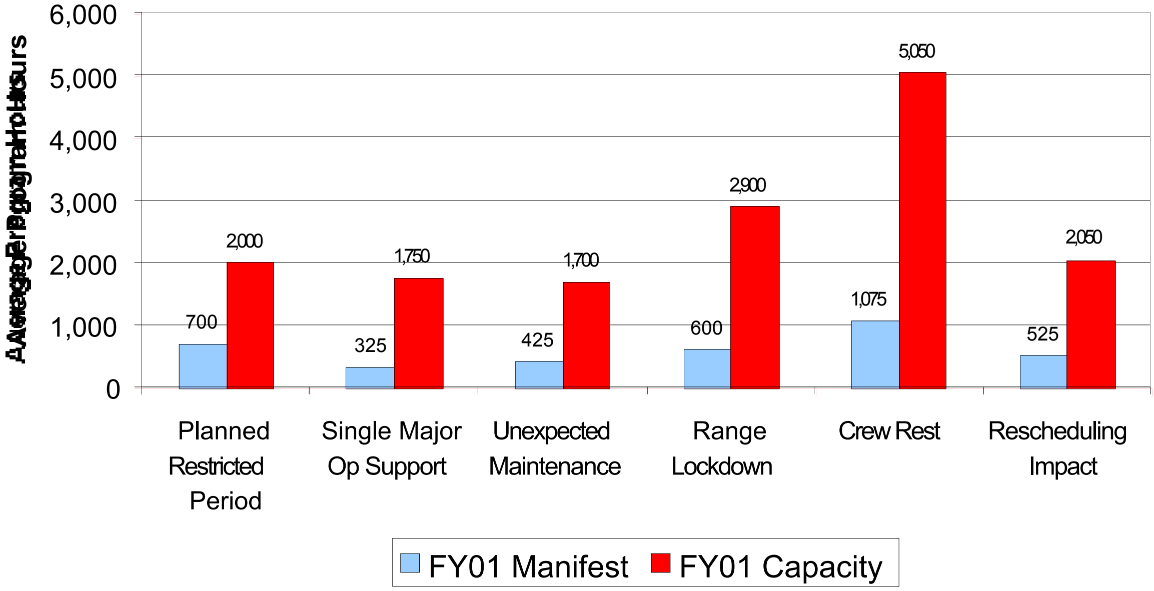

Figure 3.39: Comparison of Average Conflict Hours for FY01 Scenarios

Figure 3.40 shows the percent attribution of each of the six categories of range support conflict for the expected and capacity FY01 scenarios. These results suggest that the category of range crew rest represents the largest range constraint for FY01 regardless of whether the range will operate according to the current launch manifest or rather at capacity conditions.

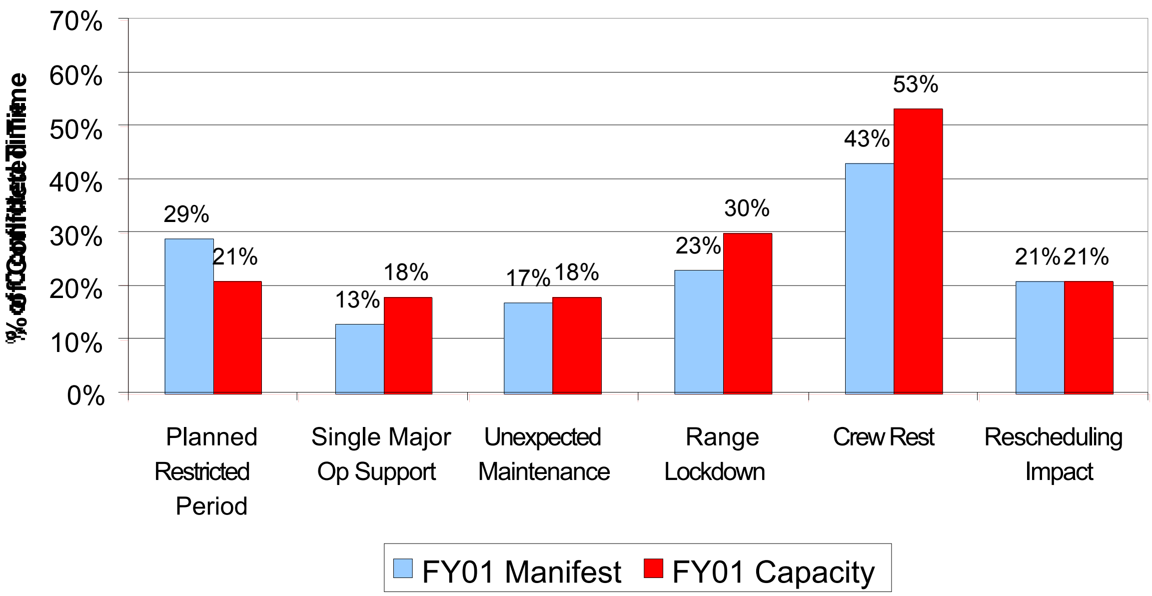

Figure 3.40: Comparison of Average % Attribution of Support Conflict Categories for FY01 Scenarios

Although the impact of each of the six categories increased in terms of absolute program hours for the range capacity scenario, the relative standing of the conflict categories does not remain consistent across both range scenarios. It was determined that as more and more launches are added to the manifest and range congestion increases that the relative impact of the planned restricted periods decreases compared to the other five categories. The relative impact due to rescheduling remained the same for both scenarios and the impact due to unexpected maintenance was found to increase very slightly. On the other hand, the categories of single major support, range lockdown, and crew rest were all found to have a higher relative impact under range capacity conditions. In summary, this observation suggests that the relative priority of concerns related to improving range launch operations depends on whether the goal is to improve the expected conditions of launch operations or instead to increase range capacity.

CHAPTER 4: POLICY IMPLICATIONS

4.1 Roles and Responsibilities

There are four main groups of participants involved with space launch operations in the United States. The U.S. Department of Defense, the Department of Transportation/FAA, NASA, and commercial launch providers all have distinct responsibilities and carry out specific space launch-related functions.

4.1.1 Department of Defense

The U.S. Department of Defense (DoD) serves as the launch agent for the defense and intelligence sectors of the government. The DoD also owns and operates both the Eastern and Western Ranges, which have historically been used for the majority of U.S. launch operations. As steward of the launch ranges, the Air Force currently has sole responsibility for funding, maintaining, and modernizing the national ranges. The DoD has a unique position in that it acts as both a provider and a customer of space launch services. The dual identity of the DoD has been beneficial as well as detrimental to the current space launch industry.

4.1.2 Department of Transportation/ Federal Aviation Administration

The Federal Aviation Administration (FAA), within the U.S. Department of Transportation (DoT), was assigned responsibility for regulating and licensing the commercial launch industry by the Commercial Space Launch Act of 1984. The Office of the Associate Administrator for Commercial Space Transportation (AST), within the FAA, has responsibility for:

- the licensing of commercial space launches and launch site operations,
- licensing the operation of non-Federal space launch sites, and
- determining insurance or other financial responsibility requirements for commercial launch activities

A *Memorandum of Agreement Among DoD, FAA, and NASA on Federal Interaction with Launch Site Operators* was signed in 1997 (DoD 1997). This agreement explains the respective roles and responsibilities of the DoD, the FAA, and NASA, in their interactions with launch site operators; however, it does not apply to operation of a launch site performed as part of a federal space activity carried out by, or exclusively for, the federal government.

4.1.3 National Aeronautics and Space Administration

The National Aeronautics and Space Administration (NASA) is responsible for the nation's civil space program. Most of NASA's space launch activities take place from the Kennedy Space Center (KSC) in Florida. This facility is adjacent to Cape Canaveral Air Force Station, operated by the Air Force, and is responsible for launching manned Space Shuttle missions from launch pads 39A and 39B. When NASA conducts unmanned missions, it usually acts as a launch customer to one of the existing commercial launch providers. In addition to its launch activities at KSC, NASA operates the Wallops Flight Facility Test Range in Virginia, which is used for aeronautical operations as well as orbital and suborbital launch operations.

4.1.4 Commercial Launch Industry

Currently there are only three U.S. commercial launch service providers, which privately operate launch vehicles capable of achieving orbit. Boeing, with its Delta family of launch vehicles, and Lockheed Martin, with the Athena, Titan, and Atlas launch vehicles, constitute the bulk of the U.S. space launch vehicle industry, while Orbital Sciences contributes launch capability with Pegasus and Taurus launch vehicles. In addition to the purely commercial launch service providers, United Space Alliance, under contract with NASA, has responsibility for some of the operations of the Space Shuttle fleet.

Although there are a number of other efforts to develop additional space launch systems, this limited collection of companies constitutes the foundation of today's U.S. space launch capability. These companies conduct launch operations, for both commercial and non-commercial customers, at facilities located on federal, state, and private sites.

4.2 National Space Law and Policy

National space law is a topic that can be broken down into a number of specialized categories. The following selections represent the primary federal policies relating to space launch. Although each selection covers a broad range of space issues, only those sections relating to launch operations and capacity are presented. In this sense, the following coverage is not meant to provide an overall background of space policy, but rather focuses on those aspects of existing U.S. policy as they relate to this thesis.

4.2.1 Commercial Space Act of 1998

The Commercial Space Act of 1998 was signed into law on October 28,1998 (1998). This legislation updated the legal framework established in 1984 by the Commercial Space Launch Act, which had already been amended once in 1988. These laws pertain to 49 U.S. Code, Subtitle IX, Chapter 701.

In 1984, the Commercial Space Launch Act introduced the concept of national launch capacity. It encouraged private sector and state government acquisition of "launch property of the United States government that is excess and otherwise not needed for public use; and launch services, including utilities, of the government otherwise not needed for public use."

The 1998 amendment was passed as an effort to update national space law so as to reflect the further need to encourage the development of a commercial space industry. Two of the purposes for this act are listed below:

- "to encourage the U.S. private sector to provide launch vehicles, reentry vehicles, and associated services"

- "to facilitate the strengthening and expansion of the U.S. space transportation infrastructure, including the enhancement of U.S. launch sites and launch-site support facilities and development of reentry sites"

Selected Congressional findings include the following:

- "Congress finds that the private sector in the United States has the capability of providing launching and reentry services that would complement services now available from the U.S. Government."

- "Congress finds that the U.S. should encourage private sector launches, reentries, and associated services and, only to the extent necessary, regulate those launches, reentries, and services."

- "Congress finds that space transportation, including the establishment and operation of launch sites, reentry sites, and complementary facilities, the providing of launch services and reentry services, the establishment of support facilities, and the providing of support services, is an important element of the transportation system of the United States, and in connection with the commerce of the United States there is a need to develop a strong space transportation infrastructure with significant private sector involvement."

As a means to assist the emerging U.S. commercial launch industry, this act dictates that the federal government shall acquire space transportation services from U.S. commercial providers whenever such services are required in the course of its activities. It also says that, to the maximum extent practicable, the federal government shall plan missions to accommodate the space transportation services capabilities of U.S. commercial providers.

The Commercial Space Act updated U.S. law by including the language of "reentry" sites, operations, and vehicles. The act also continued to task the Secretary of Transportation to "facilitate commercial space transportation activity and to promote public-private partnerships to build, expand, modernize, or operate space launch infrastructure".

In addition to updating the national legal framework, the Commercial Space Act directed the Secretary of Defense to prepare and submit a national launch capability study to Congress. This report was required to identify a number of items including the following:

1. "the resources that are necessary or available to carry out the total potential national mission model"

2. "launch property and services"

3. "the ability to support commercial launch on demand"

4. "deficiency in resources"

5. "opportunities for investment of non-Federal entities to assist the Federal Government in providing launch capabilities for the commercial space industry"

6. "technical, structural, and legal impediments associated with making launch sites or test ranges in the U.S. viable and competitive"

4.2.2 National Space Transportation Policy

Although space has not been a sustained issue of Presidential concern during the past couple of decades, the President's 1996 National Space Policy envisions that the U.S. will maintain its leadership role in the exploration and use of outer space (NSTC 1996). This White House policy mostly follows the guidance and direction of the existing national legislation without providing any unique or additional content relevant to this research. It divides space into civil, national security, and commercial sectors while acknowledging some intersection of these areas.

As a national security guideline, Presidential policy assigns the Department of Defense as the lead agency for the improvement and evolution of the current expendable launch vehicle fleet. The policy endorses national law by stating, "to stimulate private sector investment, ownership, and operation of space assets, the U.S. government will facilitate stable and predictable U.S. commercial sector access to appropriate U.S. government space-related hardware, facilities, and data." It also encourages the development of commercial space activities by saying "the government shall identify and propose appropriate amendments to or the elimination of, applicable portions of U.S. laws and regulations that unnecessarily impede commercial space sector activities."

The President maintains that fundamental to achieving national space policy goals, the U.S. will (in part):

1. "Balance efforts to modernize existing space transportation capabilities with the need to invest in the development of improved future capabilities"

2. "Promote reduction in the cost of current space transportation systems while improving their reliability, operability, responsiveness, and safety"

3. "Encourage, to the fullest extent feasible, the cost-effective use of commercially provided U.S. products and services that meet mission requirements"

4.2.3 Department of Defense Space Policy

Department of Defense Directive 3100.10 establishes policy and assigns responsibilities for space-related matters within the DoD (DoD 1999). This space policy was released on July 9, 1999 and replaced an earlier memo of DoD space policy from 1987.

This policy states that the primary DoD goal for space and space-related activities is to provide operational space force capabilities to ensure that the U.S. has the space power to achieve its national security objectives. It also mentions that contributing DoD goals include sustaining a robust U.S. space industry and a strong, forward-looking technology base. Relating to this thesis, it is interesting to point out that Department of Defense Space Policy also makes specific reference to the value of models and simulations, noting that they "shall be used to reduce time, resources, and risks of the acquisition process and increase the quality of the systems being acquired."

Stressing the utility of the space medium for national security, this policy states that space activities shall contribute to the achievement of U.S. national security objectives by assuring mission capability and access to space. Under this policy, planning for space and space-related activities shall focus on the following areas:

1. "improving the conduct of national security space operations"

2. "assuring mission support"

3. "enhancing support to military operations and other national security objectives"

The policy makes reference to the subject of commercial participation by mentioning, "stable and predictable U.S. private sector access to appropriate DoD space-related hardware, facilities, and data shall be facilitated consistent with national security requirements, in accordance with the National Space Policy and DoDD 3230.3. The Government's right to use such hardware, facilities, and data on a priority basis to meet national security and critical civil sector requirements shall be preserved." In addition, "opportunities to outsource or privatize space and space-related functions and tasks, which could be performed more efficiently and effectively by the private sector, shall be investigated aggressively, consistent with the need to protect national security and public safety."

4.3 Department of Defense Policy Implementation

4.3.1 DoDD 3200.11, Major Range and Test Facility Base (1998)

The Major Range and Test Facility Base (MRTFB) is part of the National Test Facilities Base and is a national asset that exists primarily to provide T&E information to DoD decision makers and to support T&E needs of DoD research programs and weapon system development programs. The U.S. Eastern Range is a component of the MRTFB and is therefore subject to DoDD 3200.11 (DoD 1998).

This DoD directive was reissued in 1998 and maintains that the Eastern Range is a national asset "that shall be sized, operated, and maintained primarily for DoD T&E support missions, but also be available to all users having a valid requirement for its capabilities." It designates ultimate responsibility to the Under Secretary of Defense for the acquisition of technology, test, systems engineering and evaluation, planning, programming, and budgeting process by providing estimates of operations, maintenance, and modernization requirements to accomplish projected workloads and for maintenance of this activity.

Although commercial launch providers are allowed to operate using facilities and assets of the range, the environment is viewed as "tolerant" rather than supportive of commercial launch operations. Through this policy, the DoD establishes that "MRTFB commanders are to ensure that they are not competing with U.S. private industry in providing services to commercial users or non-DoD Government users." In this sense the policy fosters further commercial development.

There are other aspects of this policy, which act as a barrier to further commercial operations on the Eastern Range. For example, consider the following two excerpts from the directive:

- "the use of MRTFB facilities by private organizations and commercial enterprises shall not increase the cost to the Department to operate the MRTFBs and shall not be factored into the decision-making process for sizing and maintaining the T&E infrastructure."

- "Commanders shall establish workable guidelines for their installations to provide some schedule stability and assurance to commercial customers and non-DoD Government users without compromising primary responsibility to DoD customers."

These clauses suggest that commercial launch providers are afforded access to the Eastern Range without effective representation. Although this situation may have been appropriate during the initial presence of commercial launch providers on national ranges, it has created considerable tension between current interests at these facilities.

4.3.2 DoDD 3230.3, DoD Support for Commercial Space Launch Activities (1986)

This DoD directive implemented several preexisting policies relating to establishment of policies, procedures, and waivers to be used in providing DoD support for commercial space launch activities (DoD 1986). The directive reiterates the following DoD policies:

1. "to encourage the U.S. private sector development of commercial launch operations"

2. "to endorse fully and facilitate the commercialization of U.S. Expendable Launch Vehicles, consistent with U.S. economic, foreign policy, and national security interests"

3. "In accordance with the "Commercial Space Launch Act" of 1984, U.S. Commercial ELV operators may be provided use of DoD-owned equipment not needed for public use or on a non-interference basis."

4.3.3 45 SWI 13-206, Eastern Range Scheduling (1996)

45th Space Wing Instruction 13-206 defines the policies, procedures, and responsibilities for scheduling operations at the 45th Space Wing (45 SW), Eastern Range (ER) (USAF 1996). It states that the objective of Range Scheduling is to ensure that all operations are scheduled and fully supported as closely as possible to the range user's requested date and time. It defines both the standard working day and standard working hours for the range.

- **Standard Working Day**- the ER working day is 8 hours daily, Monday through Friday, excluding federal holidays

- **Standard Work Hours**- 0730-1630 local time, Monday through Friday

This instruction also defines the Eastern Range scheduling priorities and procedures. It notes that the work period may vary from the standard working hours occasionally for operations support. Of particular relevance to this thesis is the following passage, as it relates to the impact of range rescheduling.

"Range users do not always reschedule a launch date when the program date has slipped. The actual reschedule sometimes lags from days to weeks after a slip is known. Range scheduling activities can be labor intensive when rescheduling occurs as all integrated and associated operations must be rescheduled. Additionally, there is significant impact on other range user's operations when moving their activities because of a change. Range users are strongly encouraged to relinquish their scheduled date and request an indefinite status when they determine that the scheduled date cannot be met. It is highly recommended to delay rescheduling of prelaunch operations until a definite launch date is determined."

4.4 Relevancy of Recent Studies and Reports

A number of recent studies have been conducted relating to U.S. space launch. Of the reports produced from these efforts, the following list was determined to contain information of particular interest and relevancy to this thesis:

- *Range Integrated Product Team Report*, 1998
- *National Launch Capabilities Study*, 1999
- *Streamlining Space Launch Range Safety*, 2000
- *The Future Management and Use of the U.S. Space Launch Bases and Ranges*, 2000

This section attempts to present the most relevant findings and recommendations from these studies related to current and future launch capacity of the Eastern Range.

4.4.1 Range Integrated Product Team Report

In February 1998, General Howell M. Estes, Commander, Air Force Space Command, directed his Director of Operations, Major General Robert C. Hinson, to form a Range Integrated Product Team (IPT) to resolve Eastern Range and Western Range operational issues raised at the December 1997 Commercial Space Industry Leaders Conference. Team membership consisted of 19 industry and 11 government organizations with a focus on achieving a greater range capacity and efficiency (USAF 1998).

In part, identified tasks for this study included:

1. Scope the capability of the DoD ranges to support a robust space launch capability over the next ten years

2. Define opportunities to increase the space launch potential through range configuration changes and streamlined processes

The study was divided into five sub-IPTs. Focused groups looked at the topics of lessons learned from foreign ranges, customer friendliness, resource use policies, range capacity, and range architecture. This report is extremely relevant to the issue of range capacity and even designated an entire section to the subject. The following bulleted items highlight the capacity-related findings and recommendations contained throughout the report. Specific information originating from the sub-IPT effort devoted to range capacity is presented as a separate section.

4.4.1.1 Selected General Findings

- "The ER is under more stress due to the burgeoning commercial space launch traffic, compounded by antiquated communications and telemetry complexes"

- "In part, the (45th Space) wing (scheduling) processes may be too slow because of disconnects between range capacity and range requirements"

- "…the ranges, no longer possessing the capacity to do the user's job, are now taking a stand that the users are fully responsible for completing their planning and delivering useable (range requirement) documents"

- "A major conclusion of the Range IPT was that, pending full implementation of range modernization, forecasted launch schedule requirements could be met with a $4.5 million dollar annual investment for a reconfiguration crew. This action would also cut the two-day turn around at the ER in half."

- "Congress passed the CSLA in 1984 as a way to encourage development of a strong commercial space launch capability. Department of Defense Directive 3230.3, published on 14 October 1986, directed that the provision of equipment and services would be on a non-interference basis using excess capacity. The implication was that DoD launches would always enjoy a priority over commercial launches. In the time frame that this directive was written, this was probably a valid consideration. An agreed definition of excess capacity was never developed. These features have combined to create an attitude of tolerance rather for commercial activities within the Air Force rather than full support. The growth of commercial space launch has well exceeded expectations to the point that the full capacity of the ranges is being challenged. The Air Force supporting organizations are being fully challenged because they have not been funded, manned nor equipped to operate the ranges at maximum capacity."

- "If the commercial launch market expands as projected, the modernization program will be essential to the preservation and growth of space launch market share."

- "Current policies, which call for the minimizing or elimination of subsidies to the commercial launch industry, are having a detrimental impact on the U.S. participation in this strong, internationally competitive industry…These policies create an environment adverse to the commercial launch industry."

- "Today, the excess capacity at CCAFS is constrained due to decreasing budgets…therefore the fundamental premises of the CSLA are now outdated."

4.4.1.2 Range Capacity Section of the IPT Report

The Range Capacity sub-IPT approach centered on the design, development, validation, and analysis of a Range Capacity Model with the following objectives:

1. Develop an AF and industry accepted definition of range capacity and the operational variables impacting range capacity

2. Develop an effective tool for range operational analysis and evaluation

The range capacity team explored four areas for potential improvement, including: schedule stabilization, pre-launch support reduction, hardware turn-around time reduction, and limited manpower augmentation. Selected findings from each of these areas are presented below.

1. Schedule stabilization

    - "Under current conditions at the ER, reducing the impact of schedule changes by 30% yields 5% annual capacity increase."

    - "Range user discipline and range use policy improvement will be necessary to stabilize scheduling processes; although the associated costs and implementation time lines are undetermined, this will probably be an ongoing effort, or evolving process of improvement."

2. Pre-launch support reduction

    - "A 30% reduction in the current amount of range time devoted to ER launch rehearsals would yield a 6% increase in annual range capacity."

    - "Although reducing support requirements may be a possible near term solution, it will more likely be ongoing due to the complex integration of range user, range operating contractor, and Range Safety involvement."

3. Hardware turn-around time reduction

    - "Reducing current turn-around times of all range subsystems on the ER by 40% will yield a 20% capacity increase."

    - "Improvement of all 12 (or at least all of the most labor-intensive) range hardware subsystems will be necessary to realize significant turn-around time reduction and capacity improvement due to the parallel nature of reconfiguration tasks."

4. Limited manpower augmentation

    - "Implementation of a core crew, with the primary responsibility of performing range reconfiguration operations, would cut ER turn-around time by 50% and increase current capacity estimates by 20%."

- "An Eastern Range core crew would consist of roughly 53 technicians, which could reconfigure range hardware in parallel with the launch personnel's crew rest period."

The team arrived at the conclusion that range capacity is a measure of merit that should be adopted as a standard for future budget and program developments and formally included in subsequent requirements documents. By establishing an initial benchmark of range capacity, the Range Capacity Model, developed for the Range IPT, supplied an excellent framework for future modeling analysis. In fact, the advanced modeling effort described in this thesis was based upon the enhancement of the methodologies used to create the Range Capacity Model.

4.4.2 National Launch Capabilities Study

Section 306(c) of the Commercial Space Act of 1998 tasked the Secretary of Defense to prepare and submit this report to Congress on the nation's launch capabilities (DoD 1999).

The *National Launch Capabilities Study* covers the subjects of U.S. launch property and services, projected U.S. launch demand, and domestic launch range capacity. Much of the information contained within the section of the report related to range capacity corresponds directly with that presented in the *Range Integrated Product Team Report*. The scope of launch capacity in this study is expanded to a national level and therefore accounts for operations conducted from other launch sites in addition to the two major national launch ranges. However, most of the capacity analysis is focused on the Eastern and Western Ranges, which are currently responsible for the vast majority of U.S. space launch efforts.

In addition to the related findings and recommendations contained within the *Range IPT Report*, the following items are of particular interest to this research effort:

- "Launch capacity is substantially intertwined with issues that can confound attempts to predict and describe range capacity. For example, natural variables such as weather patterns can impose restrictions on scheduled launches, resulting in the delay or, in cases of missions with tight launch windows, cancellation of missions."

- "Factors impacting the accuracy of launch forecasts from the demand side include, but are not limited to: changes in satellite on-orbit life expectancies, the predicted share of launch markets, future spacecraft and launch vehicle programs, selection of launch vehicle, multi-manifest variations, launch vehicle failures, satellite failures, and changes in government and non-government budgets."

- "Since range capacity is, and will continue to be, the limiting function of U.S. space launches….it is of primary concern"

- "Both ranges currently and historically devote more range time to major pre-launch rehearsals and confidence testing than to launch attempts."

- "The current Air Force budget provides for enough capacity to meet projected government launch needs (and) projected launch capacity will be sufficient to cover federal launch requirements; however, commercial launch demand could test the nation's capacity limits at the Eastern Range."

- "There is a large degree of uncertainty in both the Total Potential National Mission Model and the Theoretical Maximum Integrated Range Capacity Model."

- "The core crew concept could provide the best overall return on investment for addressing capacity needs in the near term…(and)…while (it) represents a near-term means of increasing range capacity to meet commercial as well as government needs, it is not a long-term solution."

4.4.3 Streamlining Space Launch Range Safety

The Air Force chartered the National Research Council (NRC) to review safety guidelines and procedures for government and commercial space launches at the national ranges. Subsequently, the National Research Council recently appointed the Committee on Space Launch Range Safety to examine the technologies and procedures used to provide for public safety during space launch operations and to recommend ways to reduce costs and improve efficiency without compromising public safety (NRC 2000).

Range safety is one of the primary responsibilities of a launch range. Assuring safe launch operations necessitates a considerable portion of range requirements. Therefore most changes to range safety practices and considerations will subsequently affect launch capacity. Specific observations and recommendations relating to range capacity have been extracted from the NRC report on range safety and are presented here.

- "Increasing age is also expected to increase the failure rate of critical (range support) systems and down time for repairs."

- "Coordinating launch operations with remote (downrange) facilities also complicates range safety operations and increases the risk of holds and delays (if problems occur at the remote facilities or in the communications links)."

- A large fraction of range support costs are related to developing, maintaining, and operating accurate and reliable tracking systems. EWR127-1 requires "at least two adequate and independent instrumentation data sources" for tracking launch vehicles "from T-0 throughout each phase of powered flight up to the end of range safety responsibility". For space launch vehicles, the Eastern Range implements this requirement by mandating two independent tracking sources and full FTS capability from launch through normal engine shutdown subsequent to achieving orbit.

- "Together with the results of related studies, the Air Force now has enough information to create timetables, establish priorities, assign responsibilities, and take action to improve U.S. space launch capabilities."

- "Air Force Space Command plans to implement a GPS-based flight architecture at the ER and WR, which will reduce the cost of upgrading, maintaining, and operating the radar system. A GPS-based tracking system will permit shutting down 11 of the 20 tracking radars currently used to support launch operations on the ER and WR."

- "Air Force Space Command should deploy a GPS receiver tracking system as the baseline range tracking system for space launch vehicles. The transition to GPS-based tracking should be completed as rapidly as possible."

4.4.4 The Future Management and Use of the U.S. Space Launch Bases and Ranges

An Interagency Working Group was formed in the spring of 1999 to review the future management and use of the primary U.S. space launch bases and ranges at CCAFS and VAFB. This review examines the current roles and responsibilities of federal government agencies and the U.S. commercial space sector and the major policy and management issues resulting from the shift in launch base use from its historic government-dominated basis toward more commercial, market-driven activities (OSTP 2000).

This report includes a sufficiently detailed analysis of current issues and presents a number of potential management concepts relating to operation of the U.S. launch ranges. The following comments and findings were determined to be of particular relevance to the issue of increased commercial launch operations as well as range capacity.

- "Historically, the limiting factor in U.S. launch capacity was the time required to prepare the launch vehicle and satellite on the launch pads. Over the past five years, however, government and industry have worked hard to reduce launch processing time lines as launch rates have increased."

- "Present symptoms indicate that the current workload is straining management, operations, maintenance, improvement, and modernization processes at both major launch bases and ranges."

- "Range modernization efforts are underway; however, the Interagency Working Group is concerned that range availability will remain a limiting factor on the number of launches that can be conducted annually from the U.S. launch bases and ranges."

- "Commercial range users are concerned because a high overall workload has limited the operational flexibility of the U.S. ranges, while international competition remains intense. These concerns must be addressed to continue to meet the objectives of national policy."

- "While commercial activities already account for as much as 40 percent of launch activities scheduled on the ranges, reimbursements to the government account for less than 10 percent of the costs associated with the U.S. space launch ranges."

- "The Interagency Working Group is concerned that the excess capacity constraints in the law may inhibit the future growth of the commercial space launch industry and limit the potential synergy between government private sector interests."

- "Currently DoD provides enough funding to maintain the infrastructure and personnel to support U.S. government launch activities. Because government activity is not steady, excess capacity exists."

- "In the view of commercial users, sufficient overall theoretical range capacity does not get to the heart of their concern- responding with agility to a fluid commercial market."

- "It is fundamentally the excess capacity framework that limits the ability of the U.S. government to partner fully with state governments and industry."

- "The excess capacity basis for the government-commercial relationship in current law prohibits the federal government from planning, programming, and budgeting for the commercial sector workload."

- "Agencies should develop a mechanism for evaluating requirements and determining which will be satisfied by planned federal modernization activities."

- "Next-generation range technologies will be essential to improve safety and reduce costs by orders of magnitude to enable high launch rate operations using next-generation highly reusable space transportation systems."

Selected recommendations from the report include the following:

1. Explore options for replacing the excess capacity constraint in the current policy and legal framework, while retaining priority access for national security and critical civil sector missions, to allow a more complete partnership to develop between the federal government and the U.S. commercial space sector, including states and spaceports.

2. DoD should work with all government and commercial users of the Eastern and Western Ranges to carefully reevaluate range support and operations requirements. The goal of this review is to reduce any unnecessary or outdated workload burden and improve operational flexibility and efficiency.

3. The Air Force and NASA should develop a plan to examine, explore, and proceed with next-generation range technology development and demonstration, with a focused charter to improve safety, increase flexibility and capacity, and lower costs for reusable and expendable launch vehicles.

4.5 Policy Findings Related to Launch Capacity

For over 15 years, the United States government has recognized the importance of creating a robust commercial space launch industry. Through a national policy framework the government has attempted to establish conditions for encouraging further commercial space development. In some respects, these policies have been relatively successful in achieving their goals.

U.S. commercial launch revenues are currently worth about $1 billion annually. Last year U.S. commercial launch providers conducted 13 of the 36 internationally competed commercial launches. This pace of activity tied the U.S. and Russia as the global commercial launch rate leaders, each with 36% of the launches while Europe conducted 22% of the launches (FAA 2000).

In 1982, National Security Decision Directive 42 stated that the Space Shuttle was the primary national launch capability. This decision prompted a phasing out of all U.S. government expendable launch vehicle programs. Two years later, Congress passed the Commercial Space Launch Act, which allowed the U.S. commercial launch industry to utilize the national launch ranges on an excess capacity basis. Following the loss of the Space Shuttle *Challenger* in 1986, the national policy to rely solely on the Space Shuttle was reversed. In response, Atlas, Delta, and Titan government launch programs were brought back online.

The first commercial space launch, licensed by the FAA, was conducted in 1989. The industry has grown considerably since that time. In 1997 the annual number of U.S. commercial space launches surpassed the number of U.S. government expendable launches for the first time. However, national law currently constrains the commercial launch industry by affording it access to the national launch ranges on an excess capacity basis.

As is the case for most years, including upcoming fiscal year 2001, U.S. government launches scheduled for operations at the Eastern Range will not require a constant 100 percent utilization of range resources throughout the year. Therefore, it may be concluded from this statement that excess capacity exists. Although such a finding is undoubtedly true, the policy implications are rather dangerous, given the current state of the U.S. launch industry.

U.S. Eastern Range planning, operations, maintenance, modernization, and budgeting efforts all remain as responsibilities solely of the Air Force. Given that national law prescribes commercial launch efforts to occur at national ranges on an excess capacity basis, the Air Force neither has the responsibility, authority, nor the resources to appropriately provide for the needs of the commercial launch industry at the Eastern Range. The resulting situation has caused considerable frustration to both the Air Force and space launch providers. The inability to adequately respond to the requirements and concerns of the commercial space launch market is seen as a limitation to significant further expansion of the space launch industry.

CHAPTER 5: CONCLUSION

5.1 Summary of Findings

5.1.1 Enhancements of Modeling Capability

The development of a prototype computer model was undertaken in order to explore the feasibility and potential benefits of modeling U.S. Eastern Range launch operations and capacity using a system dynamics methodology. This modeling effort utilized the existing U.S. Air Force Range Capacity Model as an initial modeling baseline. A number of data-related improvements were accomplished during the course of this research effort. The following items represent modeling improvements that were carried out during this thesis effort, but are not thought of as unique benefits of a system dynamics methodology:

- **Updated Range Support Data**
  This thesis verified and updated the range support requirements data of launch operations contained in the Air Force Range Capacity Model (December 1999 edition).

- **Individual Minor Operations**
  Range support requirements were collected and entered into the model for all individual minor operations.

The system dynamics approach was determined to offer significantly improved capabilities compared to the current Air Force spreadsheet model. The following list presents the primary modeling enhancements of the system dynamics methodology, as demonstrated in this thesis, over the existing and adopted spreadsheet approach. These specific areas, in which the system dynamics methodology enables unique capability, are divided into Launch-Related and Non-Launch-Related Enhancements:

LAUNCH-RELATED ENHANCEMENTS

- **Analysis of Expected Operating Conditions**
  In addition to modeling range capacity, the system dynamics model is configured to perform analysis of expected operating conditions or other user-defined scenarios. This feature enables comparison between expected range conditions, based on a launch forecast, and extreme operating conditions such as a range capacity scenario.

- **Range Capacity is Independent from Launch Forecasting**
  The system dynamics approach allows for a transition away from a range capacity methodology that is dependent upon a launch forecast. The suggested approach is not subject to the fluctuations and uncertainties associated with predicting future launch manifests; however, if specific portions of a launch manifest are highly certain, these launches can be imposed into the model if so desired (one could make an argument that exercising this option is a matter of *utilization of capacity* rather than strict *capacity*).

- **Competed Launch Capacity**
  A system dynamics methodology is used to calculate *Competed Launch Capacity* rather than *Supplied Launch Capacity*; therefore the system dynamics model produces a more realistic measure of range launch capacity.

  - *Supplied Launch Capacity*- considers the maximum number of launches which may be supported by the range system without regard to the throughput capability of each launch pad, or independent launch facility utilizing the range

  - *Competed Launch Capacity*- considers the maximum number of launches which may be conducted from a collection of launch pads, or independent launch facilities, utilizing a range, based not only on launch program throughput capability but also the simultaneous integration of range support requirements and restrictions

- **Sequence of Launch Operations**
  The system dynamics approach incorporates the concept that a launch campaign consists of a series of operations, which must be performed in a specified sequence (i.e. operation#1 must be conducted before operation#2).

- **Nominal Timeline of Launch Operations**
  The system dynamics approach incorporates the concept that a launch campaign consists of a series of operations, which are usually performed at specific times during a launch flow (i.e. operation#1 is planned to occur 'L-X' days before the launch).

- **Operations Flexibility**
  The system dynamics approach incorporates the concept that certain operations, within a given launch campaign, may be conducted at any point during a specified range of times without causing a delay of the launch (i.e. operation#1 can be conducted at anytime between 'L-Y' and 'L-Z' days before a tentative launch date without causing a delay of the launch).

- **Verification Through the Insight of Variables**
  The capability to view the numeric value of any variable in the model at any point during a simulation offers significant improvement in a user's ability to verify existing model relationships, potential follow-on enhancements, and any future model additions. This practice also allows the user to directly track the impacts of individual range support requirements or other chosen launch operations factors.

- **Analysis of Range Operations Constraints**
  The system dynamics model has been configured to measure the detrimental impact to range launch operations due to the following six categories of constraint: 1) *Planned Restricted Periods*, 2) *Single Major Operation Support*, 3) *Unexpected Range Systems Maintenance*, 4) *Range Lockdown*, 5) *Range Crew Rest*, and 6) *Rescheduling Impact*.

- **Endogenous Constraints**
  Endogenous modeling of the R*ange Crew Workload* and R*ange Lockdown* categories of constraint internally explains the causes of these important factors that limit launch operations. Related improvements were also accomplished for the category of U*nplanned Maintenance Activity*.

<u>NON-LAUNCH-RELATED ENHANCEMENTS</u>

- **Causal Loop Diagrams**
  The system dynamics methodology provides a sense of model structure and a visual map for tracing cause and effect relationships between variables. This is one of the primary advantages of a system dynamics approach.

- **Simulation-Based Modeling**
  The ability to run model simulations allows a user to observe the behavior of variables as trends are developed during the course of a simulation. By focusing on various time scales, a user may compare model results with known system behavior based on collected data and firsthand experience. Such an approach also provides a user with the opportunity to virtually experience future states and "what if" scenarios, rather than simply being provided with the "answer".

- **Units**
  Units are required for all values contained in the model. This practice allows users to more easily interpret the mathematical equations and therefore aids in the understanding and validation of the model. Any equation not dimensionally consistent will prompt a warning message to the user and will prevent a simulation from being performed until the error is fixed.

- **Dynamic Feedback Relationships**
  The system dynamics approach is fundamentally based on the premise of system feedback. Accounting for the critical feedback relationships of variables in any system significantly improves the capability to model a problem realistically and therefore comprehend the associated real world behavior.

- **Sensitivity Tools**
  The software used to develop the system dynamics model offers built-in sensitivity tools, which makes creating probability distributions of values simple for either input or output variables. Optimization tools are also available, but were not utilized during this research effort.

- **Help Comments**
  Helpful messages about modeled variables are quickly available to the model user and are displayed by simply moving the mouse pointer over an onscreen variable. This feature can be tailored by users of the model and assists them when being introduced to a new model or working with a large and complex model.

5.1.2 Model Results from FY01 Analysis

Two separate scenarios, corresponding to U.S. Eastern Range launch operating conditions in fiscal year 2001, were analyzed using the system dynamics model. The first scenario represented expected operating conditions and was based on the forecast of all Eastern Range launches during the FY01 period, as published in the Space Launch Manifest, which is maintained by Air Force Space Command. A second analysis was then performed based on a range capacity scenario for the FY01 period. The purpose of this second analysis was to measure the maximum range capacity for this period, to calculate the relative impact of operating constraints that essentially limit the launch capacity of the Eastern Range, and to allow for comparison between the expected operating conditions and the range capacity conditions. The following findings summarize the comparison of U.S. Eastern Range expected and launch capacity conditions for upcoming fiscal year 2001.

- **Forecasted Launch Manifest and Range Capacity for FY01**
  Thirty launches are forecasted to take place on the Eastern Range during fiscal year 2001. This value was obtained from data published as of June 1, 2000 in the Space Launch Manifest maintained by the U.S. Air Force. A system dynamics model was used to calculate Eastern Range launch capacity as a distribution of values based on the dynamic and complex interaction of operations variables. Model results suggest that the Eastern Range has a fiscal year 2001 capacity of 49 to 54 launches with varying degrees of probability. The resulting capacity distribution should not be interpreted as uncertainty due to model input parameters. In fact, this capacity distribution is entirely a function of how the real world operates. The variance of model output values that would result from changing model input values has not been examined in this thesis, but could potentially cause a significant expansion of the probability distribution. Keeping

these considerations in mind, the average value of the range capacity distribution was determined to be 51 launches. Due to current model configurations, these capacity values represent the completion of entire launch campaigns and reflect all of the various launch programs currently operating at Eastern Range facilities.

- **Expected Range Constraints for FY01**
  The system dynamics model was used to run a set of 100 simulations based on the Eastern Range FY01 launch manifest and expected operating conditions. The following findings summarize the primary results:

  - Launch Program Conflicted Time: Approximately 2,500 calendar hours of launch program wait time can be expected before the range is available to support all requests for launch operations, based on the planned activities for all launch programs. This average value was determined from a distribution of model results ranging from roughly 1,700 hours to just over 4,000 hours.

  - Sources of Conflicted Time: The range crew workload is predicted to be the largest of the six measured constraining factors of launch operations for FY01. During roughly 43% of the time that launch programs will need to wait for range support, range crew limitations are expected to be a contributing factor. The five additional constraining factors are listed according to descending impact: planned restricted periods (29%), range lockdown (23%), rescheduling impact (21%), unexpected range systems maintenance (17%), and single major operation support capability (13%). The associated actual hours for each constraint category are discussed within the body of the thesis.

  - Launch Delays: Almost 2,000 calendar hours of launch delays can be expected for FY01 when considering the planned missions of all launch vehicle programs. This average value was determined from a probability distribution of model results ranging from approximately 1,300 hours to roughly 3,500 hours.

- **Range Capacity Scenario Constraints for FY01**
  The system dynamics model was used again to run a set of 100 simulations based on an Eastern Range FY01 launch capacity scenario. The following findings summarize the primary results:

  - Launch Program Conflicted Time: Approximately 10,000 calendar hours of launch program wait time could be expected before the range would be available to support the congested flow of requests for launch operations, based on the maximization of operations for all of the major launch programs. This average value was determined from a distribution of model results ranging from roughly 8,000 hours to around 12,000 hours.

- Sources of Conflicted Time: The range crew workload is predicted to be the largest of the six measured constraining factors of launch operations if the range was operated under launch capacity conditions for FY01. During roughly 53% of the time that launch programs would be expected to wait for range support, range crew limitations would be a contributing factor. The five additional constraining factors are listed according to their expected descending impact under capacity conditions: range lockdown (30%), rescheduling impact (21%), planned restricted periods (21%), single major operation support capability (18%), and unexpected range systems maintenance (18%). The associated actual hours for each constraint category are discussed within the body of the thesis.

- Launch Delays: Approximately 7,700 calendar hours of launch delays would be expected during FY01 if the range was operated at launch capacity conditions. This value reflects the potential impact to all launch vehicle programs. This average value was determined from a probability distribution of model results ranging from approximately 6,000 hours to just over 10,000 hours.

- **Comparison of Expected and Capacity Conditions for FY01**
  The following findings summarize the major observations from comparing the expected range conditions to the maximum operations tempo of a launch capacity scenario for FY01:

  - *Range Crew Rest* is the Largest Constraint: Regardless of operations tempo, range crew rest was determined to be the most detrimental barrier, of six measured categories, to achieving increased launch operations at the Eastern Range.

  - Constraint Rankings Depend on Operations Tempo: Although the impact of each of the six measured constraint categories increases in terms of absolute hours as operations tempo increases, the relative impact of the constraints does not remain constant. The category of planned restricted periods was determined to decrease relative to the other five categories as the operations tempo increases and range congestion rises. The relative detrimental impact associated with rescheduling seems not to be affected by operations tempo; similarly, the impact of unexpected maintenance of range systems showed only slight indications of increasing. Conversely, the three remaining categories of constraint (single major operation support, range lockdown, and range crew rest) all exhibited relatively higher levels of detrimental impact as the number of scheduled operations increased. In summary, this observation suggests that the relative priority of concerns related to improving range launch operations depends on whether the goal is to improve the expected conditions of launch operations or instead to increase range capacity.

- Persistent Inefficiency of Operations: Whether the number of planned launch operations is high and approaches range capacity conditions or relatively modest, current Eastern Range constraints will result in range congestion and cause detrimental impacts to launch vehicle programs. As expected, these negative impacts become a greater concern as planned launch activity increases. The pressing concern at hand is not whether congestion exists, but rather what degrees of congestion are acceptable to the current and potential mix of range users and at what costs.

- Overlap of Launch Constraints: In many cases, there are multiple factors that prevent a launch operation from being conducted at the earliest-desired time. The frequent overlap of range support constraints, as determined in this thesis, suggests that it is unlikely for any isolated improvement effort aimed at a single constraint to resolve a significant portion of the existing congestion level of Eastern Range launch operations.

5.1.3 Policy Findings

- **National Launch Burden on the Air Force**
  Given that U.S. law prescribes commercial launch efforts to occur at national ranges on an excess capacity basis, the Air Force neither has the responsibility, authority, nor the resources to appropriately provide for the needs of the commercial launch industry at the Eastern Range. This situation has become even more burdensome in recent years, as commercial launches began to outnumber government launches on the Eastern Range in 1998.

- **Pragmatic "Excess Capacity"**
  The practical realities of a U.S. legal framework that afford commercial launch providers access to and utilization of national launch property and services on excess capacity principles unnecessarily constrain the space launch industry. As demonstrated in this thesis, the capacity of a launch range is a highly complex function with dependency on many dynamic factors. Due to the competitive nature of utilizing common range resources and the level of existing range congestion, the allocation of range support for any single launch operation is almost certainly going to have some impact to the other coexisting launch efforts. Such an interdependency of launch operations suggests that excess launch capacity is not an objective and clear operating criterion.

5.2 Recommendations

In respect to the findings presented and supported by the analysis in this thesis, the following recommendations should be considered:

- **Enhancement of the National Capability to Model Range Launch Operations**
  Each of the following areas of modeling improvement, as demonstrated by the analysis contained in this thesis and specifically presented in the section 5.1.1, should be included in the national range planning processes so as to further enhance space launch capability:

  A. Updated range support data
  B. Individual minor operations requirements
  C. Analysis of expected operating conditions or other user-defined scenarios
  D. Establishing range capacity independently from launch forecasting
  E. Sequence of launch operations
  F. Nominal timeline of launch operations
  G. Operations flexibility
  H. Verification through the insight of variables
  I. Analysis of range operations constraints
  J. Endogenous constraints
  K. Causal loop diagrams
  L. Simulation-based modeling
  M. Units
  N. Dynamic feedback relationships
  O. Sensitivity tools
  P. Help comments

- **Adoption of a "Competed Launch Capacity" Methodology as the Standard Approach to Calculating Range Launch Capacity**
  Competed Launch Capacity methodology calculates a more realistic measure of range launch capacity than the *Supplied Launch Capacity* methodology currently utilized by the Air Force. A transition of approach and the adoption of *Competed Launch Capacity* by the U.S. Government would create a more realistic launch capacity standard.

- **Continued Development of Further Modeling Capability**
  Additional modeling development is suggested. The research effort undertaken for this thesis resulted in the creation of a prototype system dynamics model focused on Eastern Range launch operations. Further model development is necessary to implement many of the enhancements realized through this exploratory research effort. In particular, considerations should be made to increasing the fidelity of modeled range support systems and related launch operations support requirements.

- **<u>Utilization of Advanced Modeling Techniques to Assess the Performance of Future and Potential Range Upgrades</u>**
  Realizing the significant amount of effort and budgets dedicated to improving near term range operations, advanced modeling techniques should be used to help quantify and assess the potential benefits of range upgrade programs. The Range Standardization and Automation program, Spacelift Range Systems Contract, and the "Core Crew" concept are examples of current modernization efforts that could receive valuable assistance and direction from an advanced range modeling capability.

- **<u>Amend the "Excess Capacity" Provision Existing in the National Space Law</u>**
  The U.S. space launch industry is unnecessarily constrained by current U.S. law, which allows commercial launch providers access to and utilization of national launch property and services on an excess capacity basis. Eliminating the "excess capacity" provision contained in the law in favor of a more equitable and promotional framework for commercial launch activities would allow for increased space launch opportunities. Current Eastern Range scheduling practices serve as an excellent example of how commercial launch operations should be given fair and just consideration. All launch provider requests for range support are processed in an identical manner. Regardless of whether the launch is devoted to a national security, civil, or commercial customer, Range Scheduling attempts to accommodate the customer primarily according to the timeliness of the scheduling request. While special consideration is reserved for the needs of critical national security and civil mission criteria, routine practice does not award any preferential treatment.

CHAPTER 6: APPENDICES

6.1 Glossary

Allocation of Range Resources- a commitment, by Range Scheduling (45 RANS/DOUS), of 45^{th} Space Wing instrumentation resources required to support an operation
Capacity- (see *Launch Capacity*)
Causal Loop Diagram- an illustration used to represent mathematical dependency (expressed as arrows) between variables (expressed as words)
CCAFS- Cape Canaveral Air Force Station
Dmnl- dimensionless
DoD- United States Department of Defense
DoT- United States Department of Transportation
Downtime- the time that a system, site, or facility is not available to support range operations; downtime is required for emergency and scheduled maintenance, engineering modification, repair, etc.
Eastern Range- Headquartered at Patrick AFB (PAFB), the 45^{th} Space Wing conducts space and missile launch operations from the central east coast of Florida. 45^{th} Space Wing instrumentation sites are located at the John F. Kennedy Space Center (KSC), Cape Canaveral Air Force Station (CCAFS), Cocoa Beach Tracking Annex, PAFB, Melbourne Beach Optical Tracking Annex, Malabar, Jonathan Dickinson Missile Training Annex, Antigua Auxiliary Airfield in the eastern Caribbean Sea, and Ascension Island in the southern Atlantic Ocean. For northerly space launches, the ER extends north to Argentia, Newfoundland, Canada. Launch sites on CCAFS are capable of supporting launch azimuths from 34 to 112. In conjunction with the National Aeronautics and Space Administration (NASA) and other DoD resources, the ER provides continuous coverage over a broad portion of the Atlantic Ocean in support of Naval Submarine Launched Ballistic Missile (SLBM) test launches and space launches.
Endogenous- internally explained and caused through the interaction of variables and agents represented within a modeled system (opposite of *exogenous*)
ER- Eastern Range
Exogenous- having an external cause and an assumed behavior not explained by relationships internal to the system (opposite of *endogenous*)
FAA- Federal Aviation Administration
Fixed Maintenance- refers to maintenance performed in response to a need for a system repair during a period not associated with launch-related operations
Inflation of a Minor Operation- additional range support is required for a minor operation, beyond the standard amount, to the level that it has an impact on range availability similar to that of a major operation

Launch Capacity- four common interpretations of "launch capacity" are presented below; this thesis argues for and utilizes the final definition of *Competed Launch Capacity*

1. **Independent Launch Capacity**- considers the maximum number of launches which may be conducted from each launch pad, or independent launch facility utilizing a range, based solely on launch program throughput capability without regard to the integration of any range support requirements or restrictions

2. **Supplied Launch Capacity**- considers the maximum number of launches which may be supported by the range system without regard to the throughput capability of each launch pad, or independent launch facility utilizing the range

3. **Exclusive Vehicle Launch Capacity**- considers the maximum number of launches of a specific vehicle type, using specified launch facilities, which may be conducted, assuming this was the only launch activity taking place, while taking into account the integration of range support requirements and restrictions

4. **Competed Launch Capacity**- considers the maximum number of launches which may be conducted from a collection of launch pads, or independent launch facilities, utilizing a range, based not only on launch program throughput capability but also the simultaneous integration of range support requirements and restrictions

Launch Flow- the time sequence of launch-related events associated with a single launch vehicle campaign
Launch Operations Facilities and Systems- those facilities and dedicated-use systems required for assembly, test checkout, and launch for satellites and launch vehicles; specifically, this includes payload and launch vehicle processing and assembly facilities, launch complexes, launch control centers, checkout control centers, associated propellant servicing systems, and other vehicle- or payload-specific facilities and systems
Launch Span- length of time from one launch to the next at a single facility
Major Support Operation- an operation that requires technical planning for range instrumentation to provide data, establishes RF radiation restrictions that affect the ER and range user; also considered a major milestone prelaunch activity when it requires major ER resources for support; the utilization of significant range support resources results in the range being able to support only one major operation at a time
Minor Support Operation- any operation support required which is not defined in operations directives and does not require a major commitment of range resources; minor support operations are normally requested when time does not allow for proper documentation and should be restricted to user needs for which a minimum of prior planning is required; the utilization of a lower amount of range support resources

results in the range being able to support simultaneous minor operations or even possibly minor operations during a major support operation

MRTFB- Major Range and Test Facility Base

Operation Flexibility- the capability to conduct a specific operation at any one of multiple opportunities, due to the ability to work other tasks in parallel

Operations Directive- a detailed operations plan prepared according to 45 SWI 99-101, *45 SW Mission Program Documents*, specifying support to be provided by the range for a particular type or series of operations

Planned Restricted Period- this is a preplanned event that renders range resources unavailable to support launch-related operations; examples include holidays, time for training exercises, and range upgrade activities

Range Capacity- (see *Launch Capacity*)

Range Crew Rest- reserved periods of time between shifts, which serve to keep workload levels of the range crew within safety guidelines

Range Lockdown- the period of time between the completion of an F-1 range reconfiguration operation and a launch, during which time the only program that may receive range support for a major operation is the program for which the range has been reconfigured for launch

Range Scheduling- the process of allocating specific periods of range time and resources for conducting an operation

Range Turnaround Time- the minimum support period interval required for range instrumentation to transition between consecutive launch support attempts or major prelaunch operations support

Range User- an agent or agency authorized to conduct operations at the Eastern Range

Rescheduling Impact- arises from the amount of time previously allocated to support range operations, which is ultimately not utilized by any launch program

Scrub- a determination to discontinue support for an operation that has been broadcast in the current Range Operations Schedule

Single Major Operation Support- by definition, a major operation requires such an extensive amount of range resources that only one major operation may be supported at any given moment

SLBM- submarine-launch ballistic missile

T&E- Test and Evaluation

Time Step- the smallest possible increment of time within a model

Unexpected Maintenance- this is unplanned maintenance, which is undertaken in response to an event and must be performed within the immediate timeframe in order to restore the range to a nominal working status

USAF- United States Air Force

VAFB- Vandenberg Air Force Base

Variable Maintenance- refers to maintenance performed in response to a need for a system repair during a launch-related operation

View- the portion of a causal loop diagram(s) contained within a single computer screen

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